DEVELOPMENT OF PHOTOVOLTAIC-DIESEL HYBRID SYSTEM DESIGN INCORPORATING ADVANCED CONTROL ALGORITHM

FINAL REPORT

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Preface

Photovoltaic-diesel hybrid systems have become an increasingly common option for supply of high quality power in remote areas. This report presents an evaluation of hybrid system design and operation, with an emphasis on battery behavior and battery-system interactions. The analysis is done using a framework of life cycle cost calculations, in order to evaluate the effect of proposed designs on end user cost of energy. The goals are to develop a battery model which can be used both in design analysis and in actual system control.

The hybrid system analysis was done using a proprietary model of IPC which looks at the hybrid system both as a whole system and as individual components. A simplified form of this model suitable for first level analysis is presented in the study.

The battery modelling is based on work done by the Electrochemical Science and Technology Centre of the University of Ottawa under contract to IPC and Westinghouse Canada, and remains the property of Westinghouse Corporation. This model was developed after extensive analysis of a selected flooded and sealed lead acid batteries at ESTCO. Parallel work was done by IPC on both these and related batteries, in order to verify applicability of the model. The results of this effort are presented in this report in equation form.

The tools and methodologies presented in this study are an example of how better understanding of the major components in a hybrid system and interaction between these subsystem can lead to reduced cost and better system control.

Abstract

Battery subsystem control is one of the most important aspects of a photovoltaic-diesel hybrid power system used to supply loads in remote areas. This control is deeply dependent on understanding both the behavior of the battery itself, and the the interactions of the battery with the remainder of the system. This study presents an overview of hybrid system design, showing what is required of the battery, along with a mathematical model of the battery and an analysis of an optimized control algorithm for a typical hybrid system. The basis for system evaluation is life cycle costing, an economic analysis technique which accounts for all costs over the life of the system in order to arrive at a final "life cycle cost of energy."

The basic goals of a hybrid system are to optimize the use of each subsystem in order to lower the net cost of energy while retaining system availability. Specific goals include minimizing the diesel running time, maximizing diesel loading, maximizing battery recharge efficiency, and maximizing acceptance of solar energy. Analysis of a mathematical model of the battery, including both discharge and bi-modal recharge models (pre- and post-gassing), shows that a high rate recharge limited only at the very end of charge is the most optimum recharge technique, and that less frequent, deep cycling of the battery is more economic from a system point of view than more frequent shallow cycling.

The models presented in this study can be used both to analyze system behavior at the design stage with a view towards system optimization, as well as directly in the system controller to provide accurate real time monitoring and control of the hybrid system. Further analysis of battery behavior and battery-system interaction will help to lower the cost of energy provided by hybrid system.

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Executive Summary

Photovoltaic-diesel hybrid systems offer an attractive alternative to other technologies for supply of high quality power to remote areas. Loads in these areas are typically supplied by diesel generators, thermal combustion of fossil fuels, or primary batteries , although renewable technologies such as solar (including photovoltaic (PV) and solar thermal) and wind are being used more frequently to supply specialized needs. A photovoltaic-diesel hybrid system allows optimal use of both the diesel generator and photovoltaic array resulting in increased reliability and lower overall costs than either technology alone.

In order to accurately compare different technologies, or to compare variations within one technology, a comparative framework must be established. Since the overall goal of power production is lowest cost for a given reliability, an economic analysis technique called "life cycle costing" was used as the framework for all comparisons in this report. Life cycle costing adds both capital costs and discounted operating costs (including fuel, maintenance and non-recurring replacement costs) over the lifetime of the system, then divides by the total energy produced to calculate a "life cycle cost of energy," typically expressed in dollars per kilowatt-hour (C$/kWh). This technique is especially appropriate to comparison of fossil fueled energy sources, which typically have minimal capital costs but extensive operating expenses, to renewable energy sources, which have high capital but virtually no operating costs.

Optimization of a hybrid system involves understanding how each of the major subsystems affect overall behavior of the system. Since a photovoltaic-diesel hybrid system is really a battery based system with recharging by the PV array or the diesel generator, the battery forms the core of system behavior. An analysis of system interactions shows a number of goals: minimize the operating time of the diesel generator, maximize acceptance of solar energy, maximize loading of the generator while operating, and minimize the number of starts of the generator, and thus the number of cycles of the battery.

A typical hybrid system, based on a residential type AC load of 25 kWh per day, was used as a baseline for design optimization. This system consists of a 11.5 kW diesel generator, a 2.5 day (84 kWh) battery, and a 4.7 kW(p) photovoltaic array. The diesel generator runs 81 times per year, with a total of 887 hours of operation, and slightly more than 2,700 hours of operation. Diesel energy supplies 56% of the annual load. Life cycle cost analysis yields a cost of energy of $1.069 per kWh. Capital cost is 55% of the life cycle cost, fuel is 14%, maintenance is 25% and replacement is 6%.

Variations on this basic design show the effect of larger and smaller diesel generators, larger and smaller batteries, and variations in solar contribution on overall system behavior. Other analyses show the effect of increased loads and of variations in economic assumption on the baseline case.

A simple comparison of two alternatives shows that an equivalent standalone PV system would have an energy cost of over $2 per kWh, while a conventional prime diesel plant for the same load would cost $1.80 per kWh.

An accurate model of the lead acid battery used in hybrid systems is essential both for system design studies and for actual control of the system once installed.

Battery behavior can be separated into two regions - discharge and recharge. The discharge region has been modeled as a linear equation based on the fact that the battery will usually be operating above 20% state-of-charge. The state-of-charge in this region can be expressed as a function of battery voltage and discharge rate (discharge current + capacity). The recharge region has two distinct areas - pre-gassing and post gassing. The pre-gassing region can be modelled as linear, between the start of charge voltage and the gassing voltage for a specific rate of charge. The post gassing region is more complex, involving an exponential function to describe both the gassing rate (growing) and voltage rise (decaying rate of change). Once again, stat-of-charge in either region can be expressed as a function of voltage and charge rate.

An analysis was done to determine the most efficient recharge algorithm, based on the battery alone, and also based on the battery - system interactions. The optimum charge methodology is a high rate constant current charge followed by tapering at a point somewhat above the gassing voltage. This can be accomplished both by a "float type" charger set at a higher setpoint than normal, or a "traction type" charge adjusted for optimum use in a hybrid system.

The model proposed can be used both for sealed and flooded lead acid batteries, although further analysis must be done to determine the effect of the proposed charge methodology on sealed batteries, which are normally less tolerant to overcharge than flooded cells.

The final system configuration is basically the same as the first system, with a larger generator to provide higher charge rates. The cost of energy of the final configuration is nearly 10% less than the initial configuration, showing the possibilities of this type of analysis for reducing costs in actual systems.

A recommended control algorithm is presented along with a basic design methodology to adapt these techniques to other loads.

Resume'

1. Introduction / Background

Increasing need for power in remote areas as well as increasing concerns over the use of traditional fossil fueled energy sources have led to a search for alternative power plant designs. These loads range from small dedicated telemetry equipment to isolated telecommunications station, and include non-commercial loads from water pumping and refrigeration up to full remote community power plants. The traditional source of energy for these applications has been diesel generators, with primary batteries used for the very smallest loads. Many systems incorporating renewable generators such as solar panels, wind turbines, and low head hydroelectric generators have been installed and studied, but detailed knowledge of the local renewable resources, along with high capital costs have served to keep applications relatively limited.

Photovoltaic (PV) technology, using solar energy to directly generate electricity via solid state PV cells, has proven to be an economical technology for many loads in remote areas. While the capital costs are quite high, PV systems are modular so they can be closely tuned to the application. In addition, PV system, consisting of an array of PV panels, a storage battery and a system controller require very little maintenance, and have a lifetime of 25 years or more, with occasional replacements of the batteries. However, as the loads get larger, the oversizing needed to ensure adequate system reliability results in massively increased costs, which are no longer offset by the almost total absence of maintenance costs. (See Section 2.8 for further details.)

Diesel generators have other strengths and problems (Section 2.9). They have very low capital costs, but the fuel and maintenance costs required to keep them in operation quickly overshadow all other costs, leading to a very high cost of energy. In addition, generators are only available in fixed sizes, and usually need to be oversized to allow for system surges and load peaks. This causes the engines to operate at low load factors, causing low efficiency, unclean operation and increased maintenance requirements.

Even a cursory examination of these two energy sources shows that their strengths and weaknesses are complementary. Where PV has a high capital cost, diesel have low initial expenditures. Where diesels use expensive hydrocarbon fuel, PV

uses the sun as its fuel. Where diesels have large maintenance costs, PV systems have almost none. Where PV systems must be oversized to account for the unreliability of the solar resource, diesel engines can be turned on and off to provide energy only when needed. Thus was born the concept of a hybrid system, incorporating both technologies to make the final power generator stronger than either of the components.

Hybrid system philosophy can also be applied to other combinations of technologies, such as wind-diesel, wind-diesel-battery, PV-Thermoelectric Generator-battery, PV-Wind, PV-wind-battery, and so on. This study is confined to the analysis of PV-diesel-battery hybrids (referred to as simply PV-diesel in the remainder of this study) that are beginning to see commercial acceptance as remote are power supplies.

Even within the PV-diesel hybrid, there are many different system configurations which will produce results. This study looks at the process of designing a hybrid system, at the major variables involved such as relative size of components, and finally at the core of the system - the battery - in order to understand how to treat it properly. The key to the battery analysis is a mathematical model of the battery discharge and recharge characteristics that can be used both as an analysis tool, and in the controller of the system itself.

A framework of life cycle costing (Section 2.4 and Appendix A) is used to provide an economic framework for decisions on system configuration.

The results of the study are a recommended system configuration and a recommended battery management algorithm to be incorporated into the system controller.

2. PV-Diesel Hybrid System Design

2.1. Design Concepts

Hybrid power systems, defined as a system incorporating more than one generating technology, are gaining in popularity in the remote power generation market. This move towards hybrids is driven by cost and reliability considerations. PV diesel hybrid power systems offer the twin advantages of reduction in capital cost when compared with a standalone PV system, and reduction in operating cost when compared with a prime diesel system. Although the complexity of a hybrid is greater than either of the standalone choices, the reduction in overall costs can potentially offset this added complexity and make the system economic. Although many different design concepts have been proposed over the past decade, the prevalent designs today are based on a central battery to supply the load, with recharge provided by the PV array and a diesel electric generator (DEG) which is run only when needed. (Figure 2-1) Hybrid systems are used to supply both commercial loads (telecommunications equipment, cathodic protection devices, etc) as well as residential energy, for both individual households and small communities.

This type of PV-diesel hybrid system consists of five major subsystems: battery, photovoltaic, diesel, load conditioning and controls.

The battery is the core of the system, since the vast majority of energy flows into or out of the battery. Battery sizes are usually specified as the number of hours (or days) that the battery is capable of supplying the average load. Typical sizes range from 8 hours to over 120 hours (five days). Flooded lead acid batteries are the most common choice, although valve-regulated lead acid batteries are becoming viable and nickel cadmium batteries are sometimes used in specialized applications.

The photovoltaic subsystem consists of a PV array, a support structure, and miscellaneous electrical harness (wire, fuses, disconnects, etc). The PV array is measured by peak wattage and by percentage contribution to the annual energy mix. Present day systems use PV contributions ranging from 10% to over 80%.

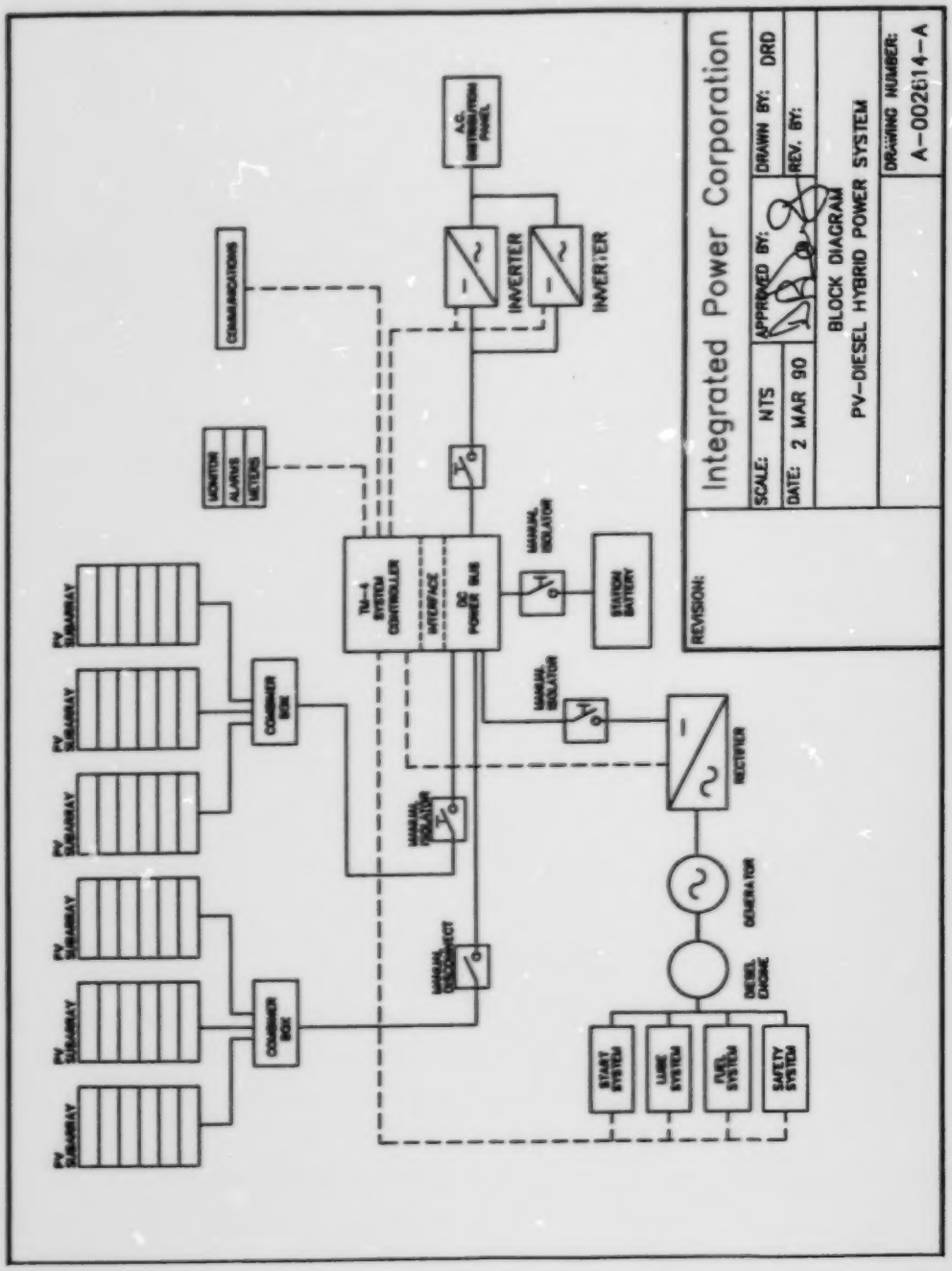


FIGURE 2-1 TYPICAL HYBRID SYSTEM BLOCK DIAGRAM

The diesel subsystem consists of a diesel engine coupled to an electrical generator, a rectifier to convert AC to DC for battery charging, fuel and associated subsystems, and electrical harness. In some cases, the DEG/rectifier combination is replaced by a diesel engine coupled directly to a DC motor which is run as a generator.

The load conditioning subsystem consists of DC power conditioning (such as filters, voltage drop devices (CEMF cells often used in telecom applications), or DC/DC converters) or AC power conditioning, commonly referred to as inverters. The load conditioning subsystem is defined by the load, which is usually referred to as either average continuous watts or a kWh per day average load. If the load is not constant, then both the average load and the peak load must be considered in the system design. Finally, the control subsystem consists of any controls needed to manage the behavior of the system. Specific tasks include PV array management, starting, stopping and monitoring of the diesel generator, control of the rectifier current and/or voltage, load conditioning, and battery management. The control system may be either centralized, with all functions performed by a single controller, or decentralized, with each device having its own control.

2.2. Load Specification

PV-diesel hybrid systems are best suited to loads in the range of 6 kWh per day to 250 kWh per day, corresponding to a continuous equivalent load of 250 watts to over 10 kW. Below 6 kWh/day a standalone PV system is usually more cost effective, due primarily to the added costs of the diesel subsystem. Above 250 kWh per day, prime diesels become increasingly cost effective, although advanced hybrid topologies are encroaching on this territory rapidly. For this study, a standard system size of 24 kWh per day AC load has been chosen.

Two major categories of loads are the constant DC load typical of dedicated telecommunications systems, and the variable AC load typical of mixed use residential systems. Figure 2-2 shows the design load profile used for the remainder of this study. The hourly average peak load is 2.2 kW, nearly twice the average load. In a residential system, the short term peak load is typically two to three times the hourly average peak load, giving a system peak load of up to 6 kW in a system with an average load of 1 kW continuous.

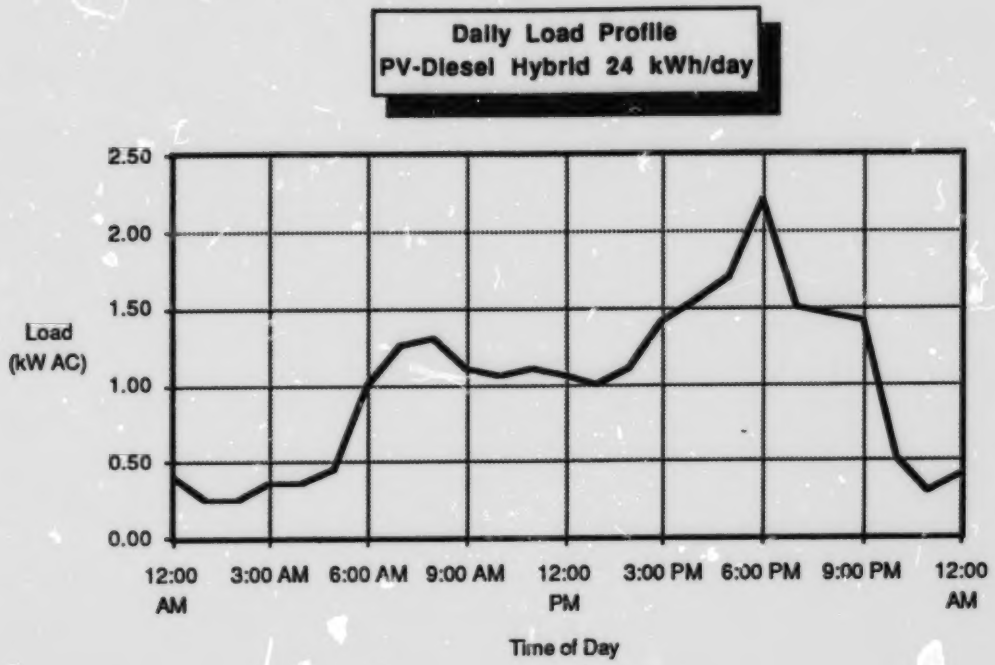


FIGURE 2-2 LOAD PROFILE - BASELINE SYSTEM

The primary effect of this peaking effect is on the battery. Batteries have varying capacities, depending on the rate at which the battery is discharged. This effect is especially noticeable at high discharge rates. Figure 2-3 shows a typical capacity vs rate curve for a commercial lead acid battery. Since the battery is rated in hours of average load, the effect of a peaking load of up to 6 times the average must be considered when analyzing the performance of the system. This effect becomes more pronounced as the battery becomes smaller.

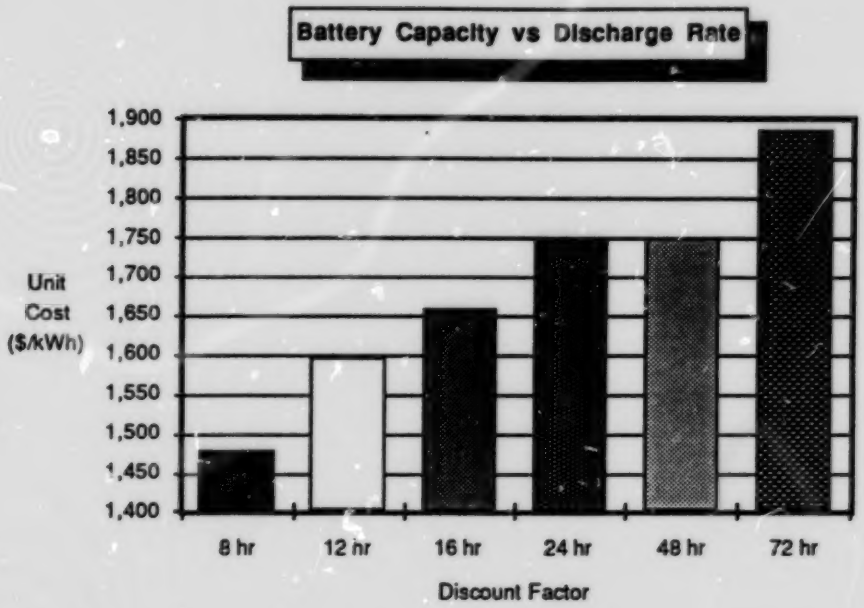


FIGURE 2-3 TYPICAL BATTERY CAPACITY CURVE

2.3. System Operation

The behavior of a hybrid system is best analyzed as a function of battery charge. Figure 2-4 shows a typical system behavior expressed as battery state of charge (BSOC) versus time. There are three distinct operational regions. The most common occurs when the load exceeds the available charging current. This region is termed "normal discharge." The second region occurs when the available energy from the PV subsystem exceeds the load, and there is thus a net charging of the battery. This region is termed "PV charging." The final region occurs when the diesel generator is supplying energy to the battery, and is termed "DEG charging." This type of chart will be used extensively in the remainder of this study to show the differences between various design conditions.

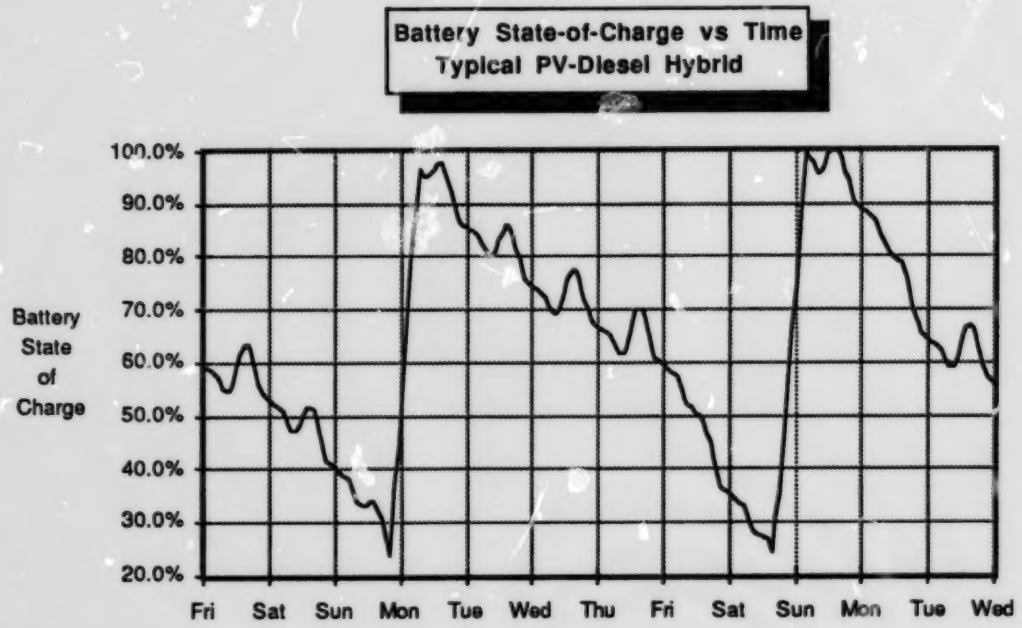


FIGURE 2-4 TYPICAL HYBRID SYSTEM BEHAVIOR

In general, since the PV array in a hybrid system is designed to supply less than the full load, the net direction of battery state of charge is down. This is especially true at night, when the PV array is contributing no energy. If the output of the PV array is greater than the load, there will be periods during the day where the battery will gain in charge for a while before resuming its downward trend. When the

battery reaches a predetermined state of charge, the diesel generator is started in order to charge the battery back up to full charge (or nearly so).

Two of the primary goals in optimizing a hybrid system design are to maximize the acceptance of PV energy and to limit the operating hours of the DEG.

The rationale behind optimizing PV acceptance is simple - PV modules are still a relatively expensive source of energy. In a standalone PV system, the array must be designed to supply the design load even during the worst insolation conditions. The result is that a great deal of energy is wasted during the summer months in order to properly serve the load during the worst case winter months. Figure 2-5 illustrates this problem. This problem is symptomatic of all passive energy sources, including solar, wind and hydro.

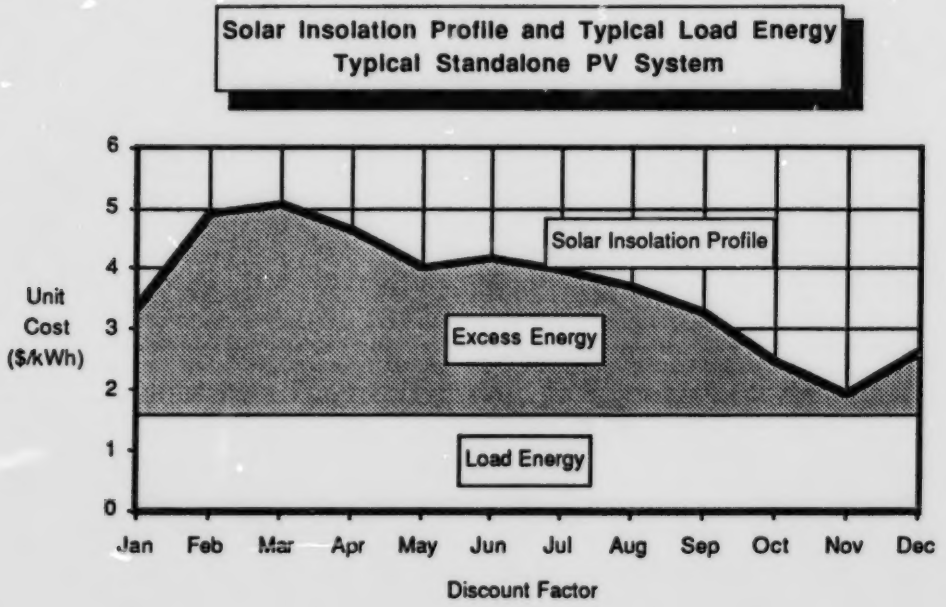


FIGURE 2-5 TYPICAL SOLAR INSOLATION VS AVAILABLE LOAD

Some definitions are in order at this point. A passive energy source is one that cannot be controlled - i.e. it can be turned off but it cannot be turned on if the resource is not available. An active energy source is one that that be turned on and off at will - the best example being the utility grid. DEGs are also an example of an active energy source. Since a hybrid is defined as a combination of

generating sources, there are three main classifications of hybrid systems - active/active, passive/active and passive/passive. A peak shaving system is an example of an active/active hybrid. In this case, a diesel generator is typically used to supply energy during the periods where the cost of DEG energy is cheaper than the peaking rates charged by the utilities. A wind/PV hybrid is an example of a passive/passive hybrid. Since both sources of energy are environmental in nature, both are passive. If the wind and solar resources complement each other exactly, either on a daily basis (e.g. solar during the day, wind at night) or on a seasonal basis (e.g. solar during the summer, wind during the winter), this type of hybrid can be very cost effective; however, if the resources are not complementary, then this type of hybrid has little net benefit.

The rationale behind limiting the number of diesel hours is less obvious. In essence, there are two types of costs associated with DEGs. This first is the fuel cost when the engine is running. Although the fuel efficiency varies dramatically based on engine loading (Figure 2-6), the net fuel efficiency of a fully loaded engine is relatively stable over a wide range of sizes. This means that the net amount of fuel that a fully loaded engine requires to deliver a given amount of energy (energy = power * time) is constant, so the size of the the energy source is unimportant.

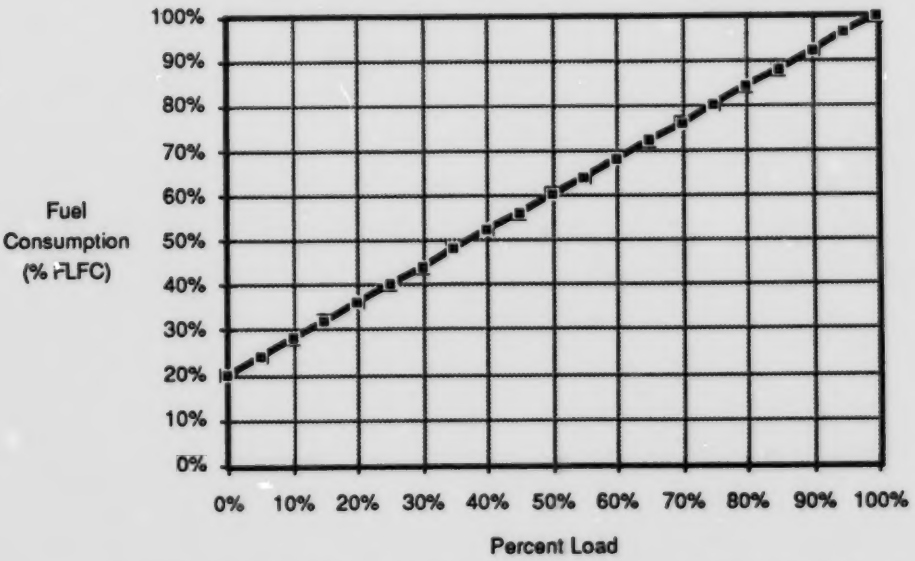


FIGURE 2-6 DIESEL ENGINE FUEL CONSUMPTION VS LOAD

The second component of DEG costs is based on maintenance, which is always tied to hours of operation. Figure 2-7 shows the maintenance requirements of a typical diesel engine. Since maintenance is based largely on hours of operation, it is beneficial to limit the number of hours that a given engine runs in order to reduce operating costs.

Period	*Item*
250 hours	Change oil in normal engine, including all filters
750 hours	Change oil in engine with long run lube, incl filters
1,500 hours	Do decarbonization on engine (top end overhaul), replace gaskets, reseat valves, clean/replace fuel injector /nozzle as necessary
6,000-10,000 hours	Full overhaul, replace all bearings and gaskets, replace injectors, rebuild fuel pumps as necessary

FIGURE 2-7 DIESEL MAINTENANCE SCHEDULE

2.4. Life Cycle Cost Analysis

One of the problems which occurs when trying to compare generating options based on active and passive energy sources is that the passive option (such as solar) often has a large initial cost coupled with negligible operating costs while an active system (such as a DEG) usually has a low initial cost, but has high fuel and operating costs.

Life cycle cost analysis is a tool used to help compare the relative benefits of differing generating options. LCC analysis counts initial costs as well as operating costs in developing the cost of energy of a system over the net lifetime of the system. The four basic components of a life cycle cost analysis are: capital cost, fuel related operating costs, maintenance (non-fuel) operating costs, and replacement of subsystems over the life of the system. The operating costs of the system are inflated over the life of the system in order to model increasing costs, while annual costs are discounted over the years to allow for the change in the value of money. With the initial cost and each year's operating cost summed up over the life of the system, the total cost of operating the system for a given period of time can be determined.

This study uses LCC analysis as a basic tool for comparing differing options in system design. The exact method used to determine life-cycle-cost is described in Appendix A.

2.5. Basic System Design

In order to provide a systematic comparison of differing design options, it is necessary to choose a system to serve as a baseline from which variations can be measured. The baseline system used in this study is designed to supply the 24 kWh/day AC load described in Section 2.2. The system consists of an 84 kWh battery (1750 Ah at 48 VDC), a 4.7 kW(p) PV array (consisting of 100 PV modules, each rated at 47 W(p), configured as 25 parallel strings of 4 series modules each), an 11.5 kW DEG with a 145 A rectifier, and a 6 kVA inverter. In the most basic configuration, the PV array supplies 44% of the annual energy requirement based on an average insolation value of 3.86 kWh/day (Figure 2-8). The DEG (modeled after a Lister TR-2 two cylinder air cooled model) starts 103 times per year, for a total operating time of 902 hours per year. Annual fuel consumption is 2,723 liters per year based on a full load fuel consumption of 3.7 liters per hour. Details of the basic system design and performance are given in Appendix B.

Maintenance requirements call for oil changes approximately twice per year, and for decarbonizations once per year. Overhauls are required approximately once every six years, and the engine should last for the 25 year design life of the system.

Maintenance on the rest of the system requires one visit per year (which is coordinated with other visits) to check battery electrolyte levels and perform basic cleaning and other maintenance tasks. The batteries have a design lifetime of 9 years (based on a cycle life of 1,000 cycles to 60% DOD), and so will need to be replaced twice during the lifetime of the system.

Figure 2-9 shows an electrical schematic of a typical system.

The performance summary of the baseline system is shown in Figure 2-10.

The energy contribution of both ***solar*** and ***diesel*** is broken out by month in Figure 2-11.

The capital cost of the baseline system is $128,065, including shipping, installation, and project management. (Note shipping and installation are estimated to be $2,000 and $4,000 respectively. Engineering and project management total

approximately 10% of the overall capital cost.) The breakout of the major capital cost components is shown in Figure 2-12.

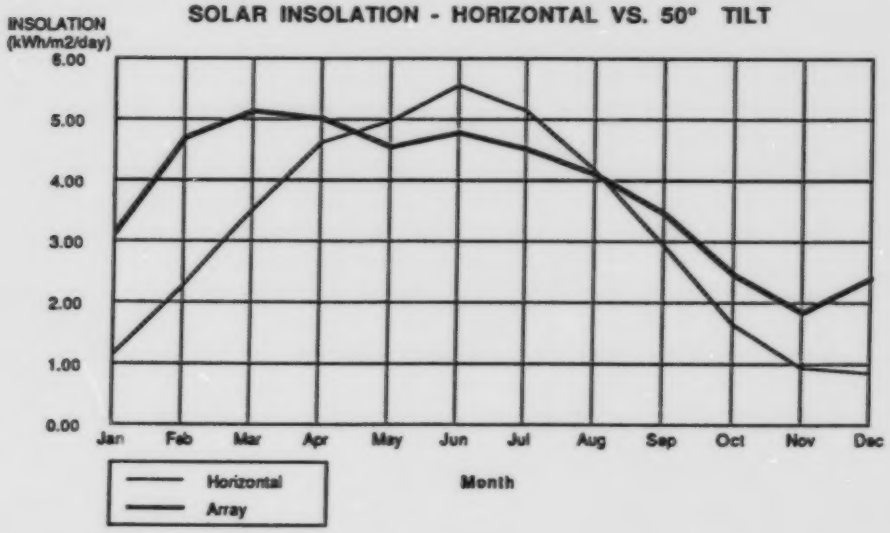
The life cycle unit energy cost over the standard twenty 25 period is $1.07 per kWh, as shown in Figure 2-13. Figure 2-14 shows the various components of the life cycle cost in graph form. All costs are based on commercially available components and are expressed in Canadian dollars. Where derived from US currency, and exchange rate of C$1.00 = US$0.85 was used.

SOLCAD® TILT CORRECTION MODULE

CITY: Moosonee **STATE:** Ontario **COUNTRY:** Canada
LATITUDE: 52°00' N **LONGITUDE:** 81°00' W **TILT:** 50° South facing
COMMENTS: From Canada Climate Normals

MONTH	HORIZONTAL INSOLATION (kWh/m2/day)	TILT FACTOR	ARRAY INSOLATION (kWh/m2/day)
Jan	1.16	2.70	3.13
Feb	2.25	2.09	4.70
Mar	3.49	1.48	5.16
Apr	4.62	1.09	5.04
May	4.98	0.91	4.55
Jun	5.57	0.86	4.79
Jul	5.14	0.88	4.54
Aug	4.18	0.99	4.12
Sep	2.93	1.19	3.48
Oct	1.66	1.49	2.47
Nov	0.94	1.97	1.86
Dec	0.86	2.82	2.42

WORST CASE: Nov 1.86
AVERAGE: 3.85



INTEGRATED POWER CORPORATION
7524 STANDISH PLACE
ROCKVILLE, MARYLAND 20855 USA

TELEPHONE :301-294-9133
FAX :301-294-0809
TELEX :79-7799

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FIGURE 2-8 SOLAR INSOLATION SUMMARY

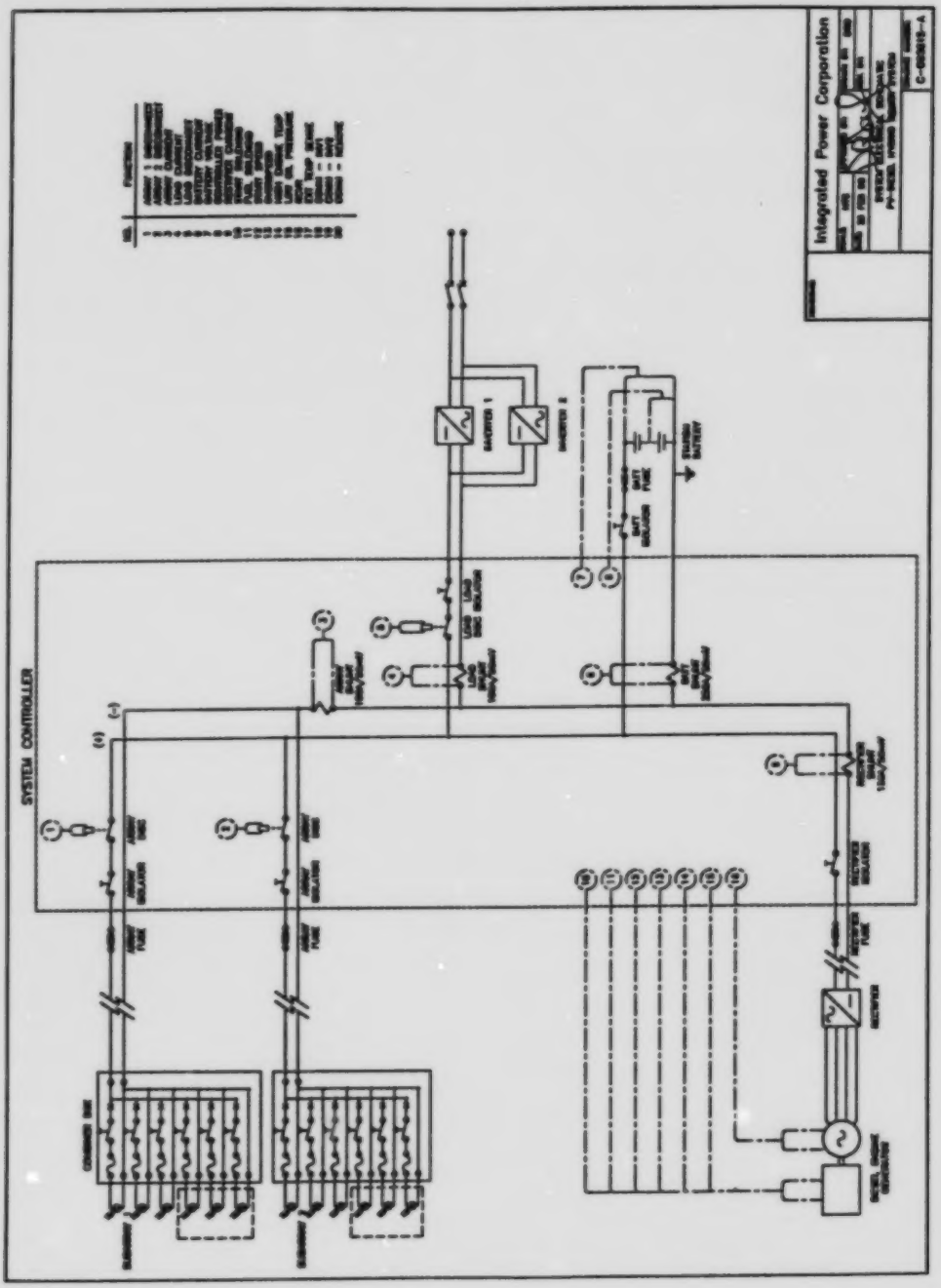

FIGURE 2-9 HYBRID SYSTEM ELECTRICAL SCHEMATIC

SOLCAD - RAPS Remote Area Power Supply Sizing Program

Integrated Power Corporation - copyright 1990

System Summary

Site:	Moosonee, Ontario, Canada		
Date:	23 Mar 90		
Load:	24 kWh/day @	120 V AC	
Battery:	Type	E120-29	
	Voltage	48 V DC	
	Amp-hrs	1750	@ 72 hr rate
	Capacity	2.6 days	
		84 kWh	
PV Array:	Module	M-47	47 W(p)
	# of Modules	100	
	Array Rating	4.70 kW(p)	
Diesel Genset:	Type	Lister TR2	
	Rating	11.5 kWe	
	Frequency	60 hz	
Wind Turbine:	Type		
	Rating	0.0 kW	
Diesel Performance	Cycles	81	
	Hours	887	
	Fuel Use	2,702	
Energy Contribution	PV	44.2%	
	Wind	0.0%	
	Diesel	55.8%	
Cost Information	Capital	$128,065	
	Operating	$5,321	
	Life Cycle	$1.069	

FIGURE 2-10 PERFORMANCE SUMMARY - BASELINE SYSTEM

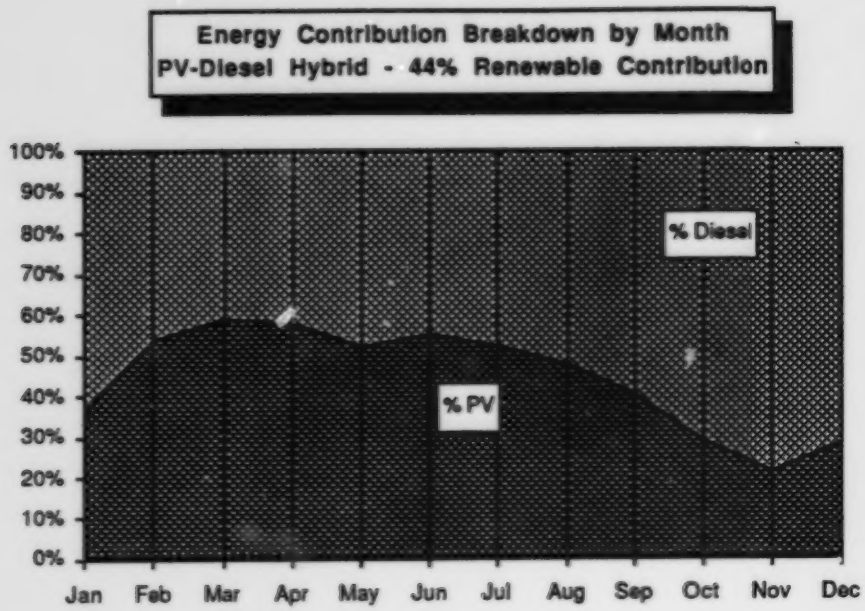

FIGURE 2-11 ANNUAL PERFORMANCE - BASELINE SYSTEM

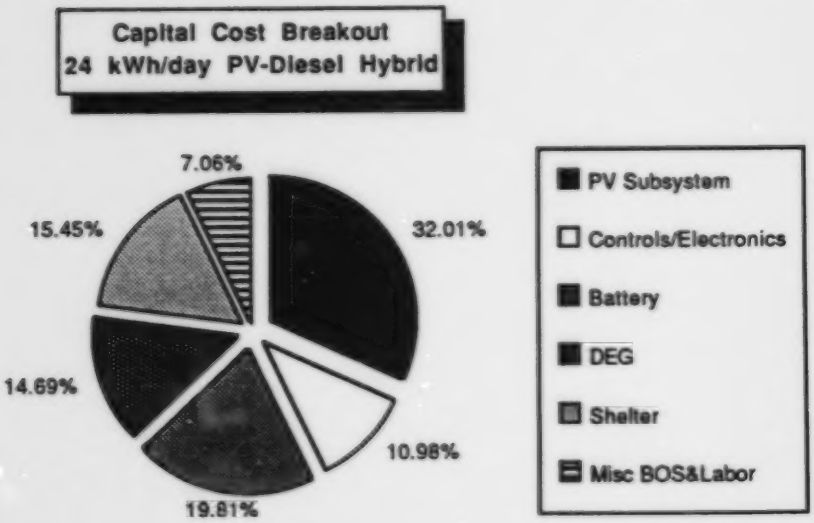

FIGURE 2-12 BASELINE SYSTEM CAPITAL COST

LIFE CYCLE COST ANALYSIS © IPC 1989

Description	24 kWh/day Hybrid Baseline System
Analysis Period	25 yrs

Components	$112,065
Shipping	$2,000
Installation	$4,000
Distribution	$0
Project Management	$10,000
Total Capital	$128,065
% Financed	0%
Amount Financed	$0
Loan Term	25 yrs
Loan Interest	10.0%
Loan Payments	$0
Energy Produced	24 kWh/day

Discount Rate	10.0%
Fuel Escalation	8.0%
Fuel Esc Ratio	0.982
Non-Fuel Escalation	6.0%
Non-Fuel Esc Ratio	0.964
Fuel Use	2,702
Fuel Cost per Litre	$0.60
Recurring Fuel	$1,621
Recurring Non-Fuel	$3,699

Non-Recurring Item	Amount	Year
Battery	$23,824	13

Item	Amount	Year	Factor	LCC
Capital	$128,065	0	1.000	$128,065
Loan Payment	$0	all	25.000	$0
Recurring Fuel	$1,621	all	19.867	$32,209
Recurring Non-Fuel	$3,699	all	16.003	$59,194
Battery	$23,824	13	0.618	$14,719
	$0	0	1.000	$0
	$0	0	1.000	$0
	$0	0	1.000	$0
	$0	0	1.000	$0

Total LCC	$234,187
Total Energy	219,000
Unit Cost	$1.069

FIGURE 2-13 BASELINE SYSTEM LIFE CYCLE COST WORKSHEET

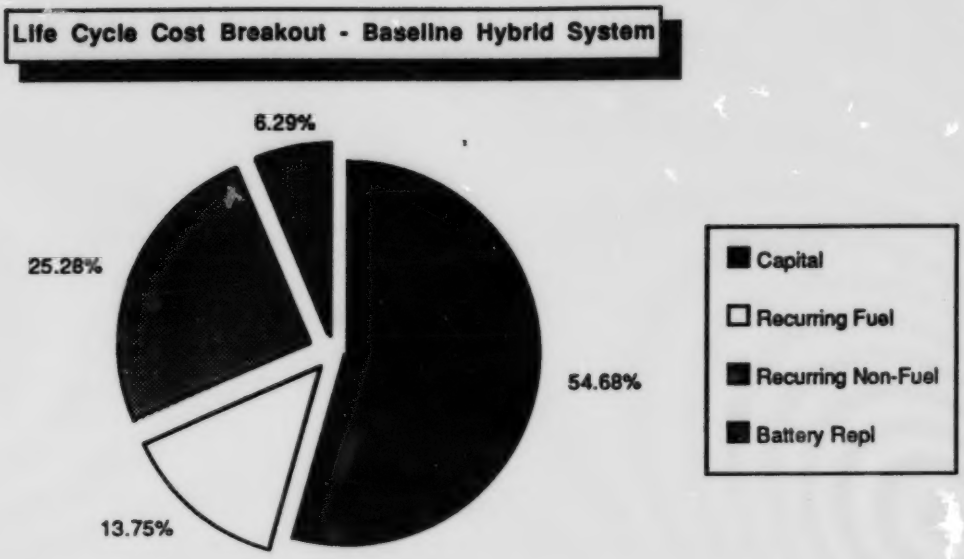

FIGURE 2-14 BASELINE SYSTEM LIFE CYCLE COST

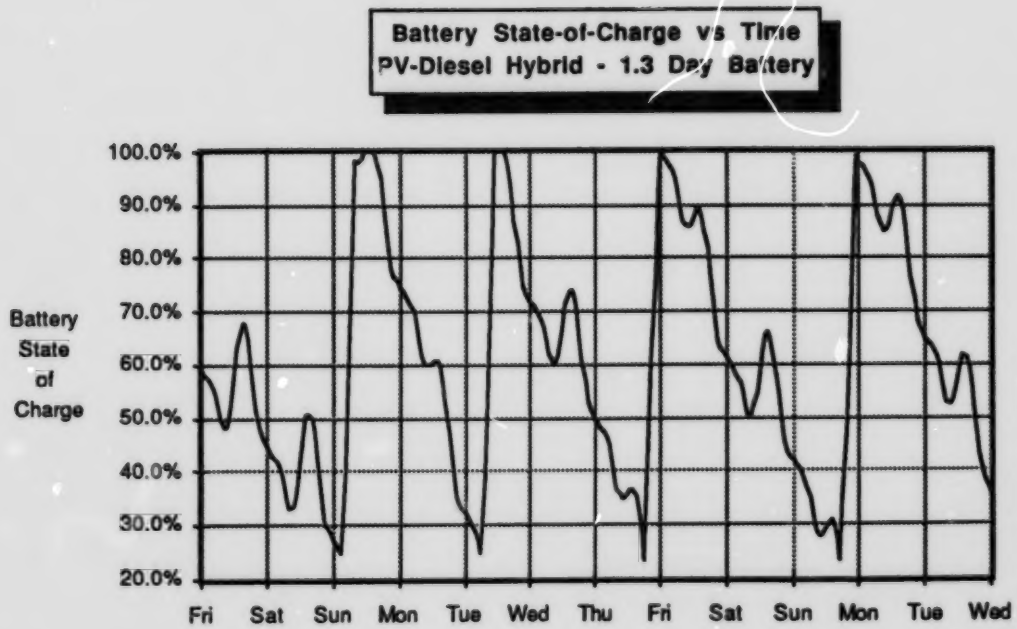

FIGURE 2-15 SYSTEM BEHAVIOR - 1.3 DAY BATTERY

2.6. System Tradeoffs

In order to develop an optimum design for a hybrid system, it is useful to study the effect of varying the sizes of major subsystems. The effect is best shown as a variation in system cost (illustrated by life cycle unit energy cost) and a variation in system behavior as shown by BSOC vs time graphs. This section shows the effects of varying battery size, generator size, PV array size (and thus renewable contribution) and the effect of changing loads.

2.6.1. Battery Size

The size of the battery in a cyclic hybrid system has a first order effect only on the frequency of battery charging cycles - the smaller the battery, the more frequent the cycles will be. This can have a direct effect on the life of the battery in that the battery has a cycle life as well as a calendar life. If the number of cycles is increased, the battery will not last as long. Battery size also has a secondary effect on maintenance costs, in that the generator must start more frequently with a smaller battery, so there is a higher probability of start failure. On the other hand, if the battery is too large, the generator will not be called upon often enough, and might fail to start due to inactivity when called upon. This is the reason generators are usually "exercised" when they are used in standby functions.

The size of the battery also limits the maximum charge current which can be used, which in turn limits the size of the generator, and thus the annual maintenance costs.

Finally, the size of the battery affects the ability of the system to absorb expanded loads. A system which is designed too tightly at the start will not be able to cope with increases in load which are part of the normal growth process.

Figure 2-15 shows the BSOC vs Time curves for a system with half the battery of a standard system. Figure 2-16 shows the performance summary for the same system.

SOLCAD - RAPS Remote Area Power Supply Sizing Program

Integrated Power Corporation - copyright 19.0

System Summary

Site:	Moosonee, Ontario, Canada		
Date:	23 Mar 90		
Load:	24 kWh/day @	120 V AC	
Battery:	Type	E120-29	
	Voltage	48 V DC	
	Amp-hrs	875	@ 24 hr rate
	Capacity	1.2 days	
		42 kWh	
PV Array:	Module	M-47	47 W(p)
	# of Modules	100	
	Array Rating	4.70 kW(p)	
Diesel Genset:	Type	Lister TR2	
	Rating	11.5 kWe	
	Frequency	60 hz	
Wind Turbine:	Type		
	Rating	0.0 kW	
Diesel Performance	Cycles	176	
	Hours	887	
	Fuel Use	2,702	
Energy Contribution	PV	44.2%	
	Wind	0.0%	
	Diesel	55.8%	
Cost Information	Capital	$115,866	
	Operating	$6,531	
	Life Cycle	$1.066	

FIGURE 2-16 PERFORMANCE SUMMARY - 1.3 DAY BATTERY

2.6.2. Generator Size

The size of the generator effects the maximum current that can be used to recharge the battery, and thus the running time of the generator during each charge cycle. This occurs as a result of the fixed amount of energy which the array can provide annually. All of the rest of the energy must be provided by the diesel generator. Energy is defined as the product of power and time, so time varies inversely to the power (or size) of the generator. Since of the major design goals of a hybrid system is to limit the number of hours of operation of the diesel generator, a larger generator is preferable to a small one.

The maximum size of the generator is limited by the maximum charge current which the battery will accept - generally C/5, or one fifth of the capacity of the battery. Figures 2-17 and 2-18 show the performance summary for a system with a generator half the size and twice the size of the baseline system, respectively.

SOLCAD - RAPS Remote Area Power Supply Sizing Program

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System Summary

Site:	Moose Lake, Ontario, Canada		
Date:	23 Mar 90		
Load:	24 kWh/day @	120 V AC	
Battery:	Type	E120-29	
	Voltage	48 V DC	
	Amp-hrs	1750	@ 72 hr rate
	Capacity	2.6 days	
		84 kWh	
PV Array:	Module	M-47	47 W(p)
	# of Modules	100	
	Array Rating	4.70 kW(p)	
Diesel Genset:	Type	Lister TR1	
	Rating	5.8 kWe	
	Frequency	60 hz	
Wind Turbine:	Type		
	Rating	0.0 kW	
Diesel Performance	Cycles	75	
	Hours	1,628	
	Fuel Use	2,647	
Energy Contribution	PV	44.2%	
	Wind	0.0%	
	Diesel	55.8%	
Cost Information	Capital	$128,065	
	Operating	$6,553	
	Life Cycle	$1.159	

FIGURE 2-17 PERFORMANCE SUMMARY - SMALL DIESEL

SOLCAD - RAPS Remote Area Power Supply Sizing Program

Integrated Power Corporation - copyright 1990

System Summary

Site:	Moose Lake, Ontario, Canada		
Date:	23 Mar 90		
Load:	24 kWh/day @	120 V AC	
Battery:	Type	E120-29	
	Voltage	48 V DC	
	Amp-hrs	1750	@ 72 hr rate
	Capacity	2.6 days	
		84 kWh	
PV Array:	Module	M-47	47 W(p)
	# of Modules	100	
	Array Rating	4.70 kW(p)	
Diesel Genset:	Type	Lister TR3	
	Rating	17.3 kWe	
	Frequency	60 hz	
Wind Turbine:	Type		
	Rating	0.0 kW	
Diesel Performance	Cycles	85	
	Hours	526	
	Fuel Use	2,636	
Energy Contribution	PV	44.2%	
	Wind	0.0%	
	Diesel	55.8%	
Cost Information	Capital	$129,643	
	Operating	$4,000	
	Life Cycle	$0.979	

FIGURE 2-18 PERFORMANCE SUMMARY - LARGE DIESEL

2.6.3. Renewable Contribution

The renewable contribution of this system is determined by the size of the PV array attached, and has effects on the number of battery cycles, (and thus diesel starts), diesel fuel consumption, and diesel hours of operation (and thus maintenance costs). The lower limit - no renewable contribution - is termed a cycle charge diesel and is characterized by a diesel which starts frequently, and batteries which are heavily cycled. The practical upper limit is approximately 75-80% renewable, and depends to a certain extent on the solar insolation profile for the sight chosen. If there is too much renewable content, some of the energy will need to be regulated away, thus increasing the life cycle costs of the system.

The other prime determinant for the amount of renewable used is the life cycle cost of the system. In some locations, it is more economical to put in less PV due to cost reasons, in other sites where diesel fuel is very expensive or maintenance is limited to only one season per year, it makes sense to put in more PV.

A secondary effect of the renewable content is on system behavior. If there is too much renewable, the generator will not start frequently enough to maintain top shape, and will need to be exercised.

Figures 2-19 and 2-20 show the life cycle cost and capital cost as a function of renewable energy percentage. In general, adding renewable contribution is a balancing game between increased capital cost and decreased maintenance costs. This is also dynamic, since PV modules can be added to a system later, at a much lower cost.

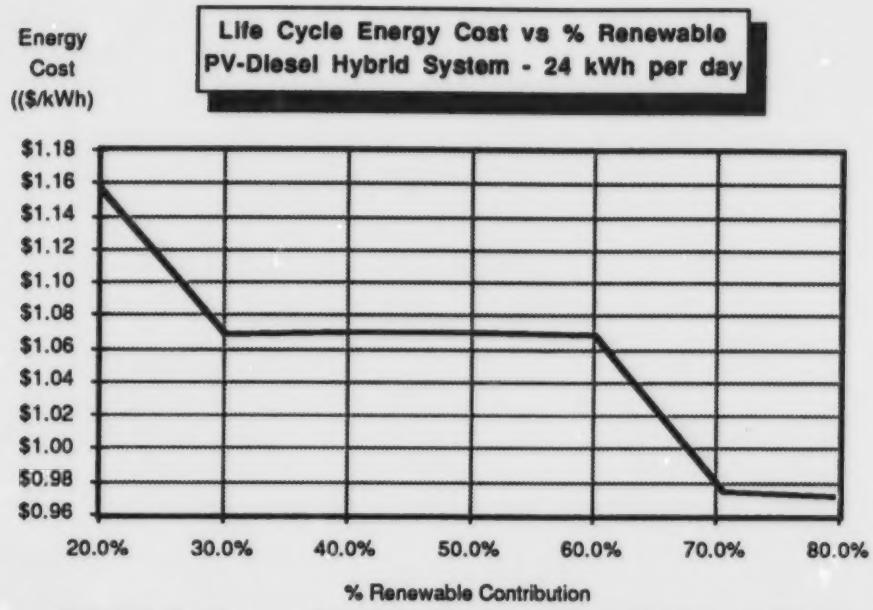


FIGURE 2-19 ENERGY COST VS RENEWABLE CONTRIBUTION

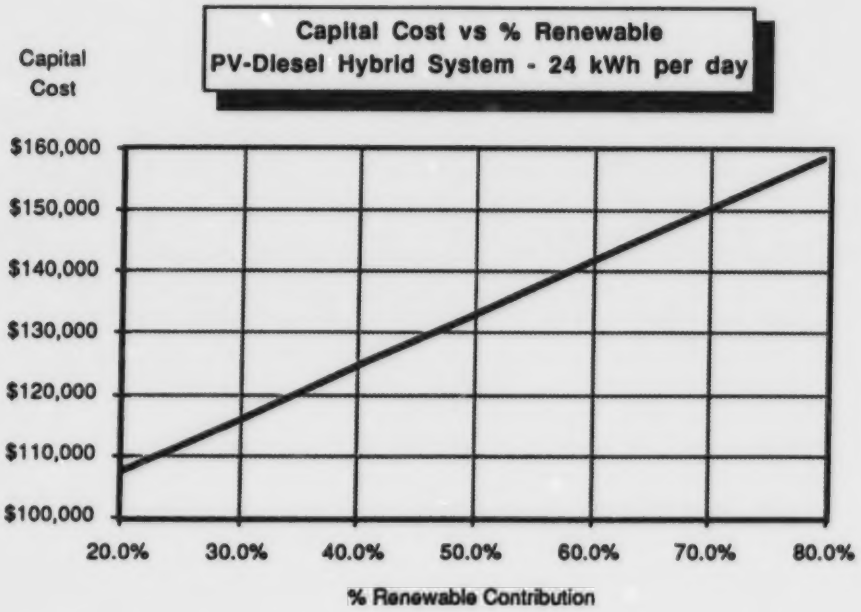


FIGURE 2-20 CAPITAL COST VS RENEWABLE CONTRIBUTION

2.6.4. Load Changes

A final aspect on system performance is the magnitude of load changes over the life of the system. In the case of a telecommunications load with very few changes anticipated over the life of the system, the design can be much tighter. However, in the case of a residential system, the load could easily increase by 50% or more. In this case, the system needs to be designed with more latitude for expansion. The residential case has another limitation based on the size of the inverter. If the inverter is upgraded to a larger unit, there will be more current draw on the batteries. If the battery was designed at its limit with the smaller inverter, there could be problems with low voltage transients causing problems during load peaks. These transients are caused by the reduced capacity of batteries at higher discharge rates, and manifest themselves as a lowering of voltage in the system. This could cause false starts from the generator, or actual load interruptions if the voltage falls below the window for inverter operation.

Figure 2-21 shows a BSOC vs time curve for the baseline system with a 50% increase in daily load. Figure 2-22 is the representative performance summary for the same scenario.

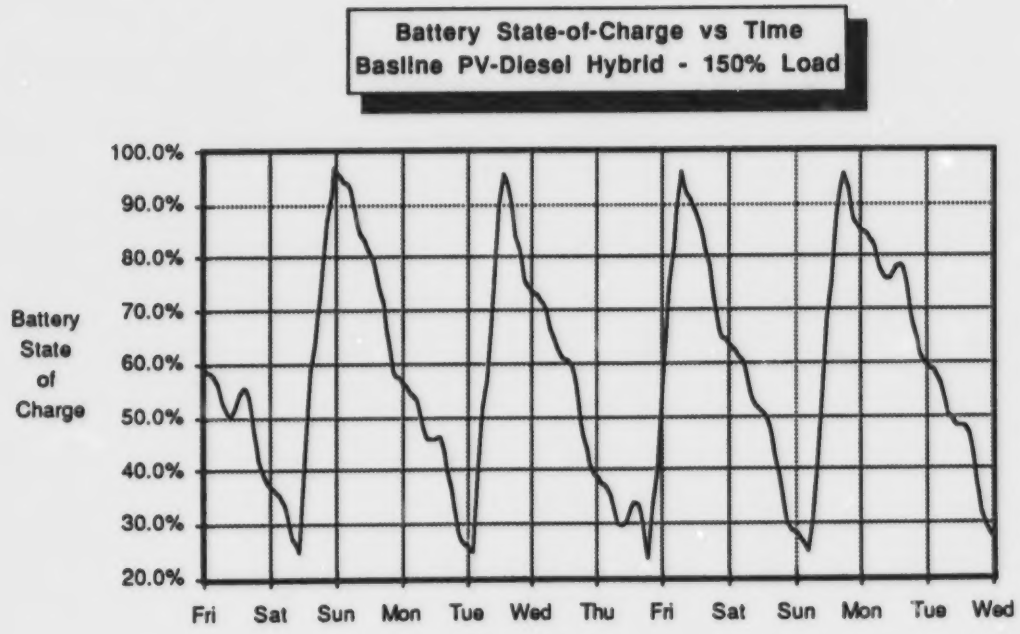


FIGURE 2-21 SYSTEM BEHAVIOR - 150% LOAD

SOLCAD - RAPS Remote Area Power Supply Sizing Program

Integrated Power Corporation - copyright 1990

System Summary

Site:	Moosonee, Ontario, Canada		
Date:	23 Mar 90		
Load:	36 kWh/day @	120 V AC	
Battery:	Type	E120-29	
	Voltage	48 V DC	
	Amp-hrs	1750	@ 24 hr rate
	Capacity	1.6 days	
		84 kWh	
PV Array:	Module	M-47	47 W(p)
	# of Modules	100	
	Array Rating	4.70 kW(p)	
Diesel Genset:	Type	Lister TR2	
	Rating	11.5 kWe	
	Frequency	60 hz	
Wind Turbine:	Type		
	Rating	0.0 kW	
Diesel Performance	Cycles	150	
	Hours	1,681	
	Fuel Use	5,127	
Energy Contribution	PV	29.5%	
	Wind	0.0%	
	Diesel	70.5%	
Cost Information	Capital	$126,382	
	Operating	$9,022	
	Life Cycle	$0.902	

FIGURE 2-22 PERFORMANCE SUMMARY - 150% LOAD

2.7. Sensitivity Analysis

In any techno-economic analysis, certain assumptions are necessary that do not necessarily apply to every conceivable case. For this reason it is necessary to do a sensitivity analysis on the major assumptions. In a multi-dimensional problem such as this, it is best to vary only one or at most two assumptions at a time. This section looks at sensitivity of the design and analysis to fuel cost, cost of PV modules, and economic factors including discount rate, fuel inflation, and non-fuel inflation.

As expected, the life cycle costs of the system is sensitive to cost of fuel, however, this sensitivity is relatively low. Tripling the fuel cost from $0.50 to $1.50 raises the life cycle energy cost by only 25%. This is because the overall cost of fuel forms only a small percentage (less than 14% - reference Figure 2-14). In a prime diesel system (ref. Section 2.9), fuel accounts for nearly half of the life cycle costs (reference Figure 2-34), so sensitivity will be much greater. The net trend in diesel fuel costs is up, and dramatic increases can be expected as crude oil reserves begin running out in the future.

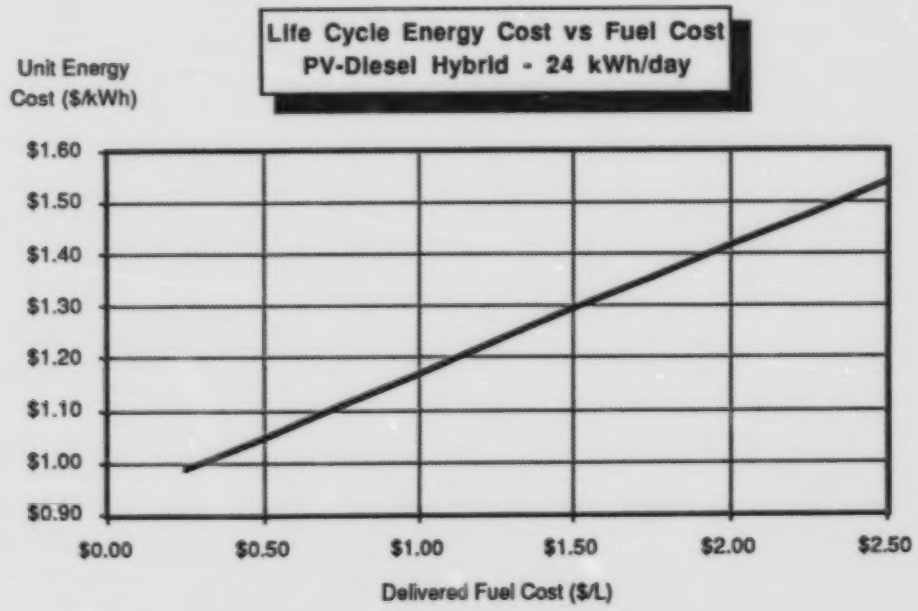


FIGURE 2-23 COST SENSITIVITY TO FUEL COST

Hybrid system costs are also sensitive to the cost of the PV modules (Figure 2-24), although even less so than to diesel fuel cost. The net direction of PV module prices has been downward, although there are occasional market corrections where prices increase for a short while. The designs used in this study are based on commercially available crystalline power modules. Although other technologies, especially amorphous silicon, are beginning to be seen in the market place, these modules do not have the power density, output stability, or reliability record of the power modules using crystalline cells. Therefore, near term price reductions will come from increased manufacturing volume and improved manufacturing techniques, while the new technologies (a-Si, other thin films, advanced ribbons, etc) will only begin to play a part in the future.

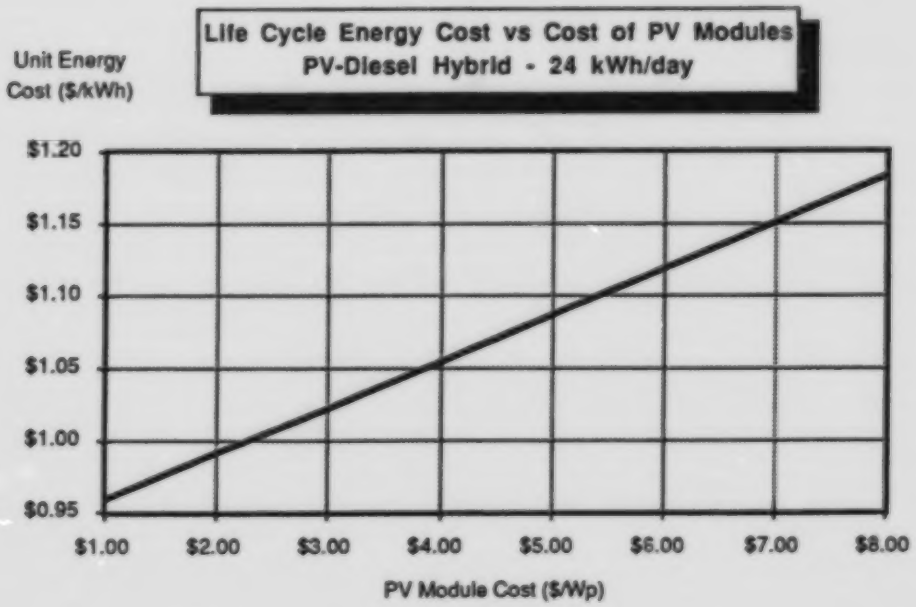


FIGURE 2-24 COST SENSITIVITY TO PV MODULE COST

The life cycle cost calculations are also sensitive to the assumptions used in the economic model used to determine the costs. The three major economic assumptions used in the life cycle costing model are discount rate, fuel inflation, and non-fuel inflation.

The effect of the discount rate on energy cost estimates is shown in Figure 2-25. The life cycle energy cost decreases with increasing discount rate. Most analyses are run with discount rates ranging from 8% to 14%.

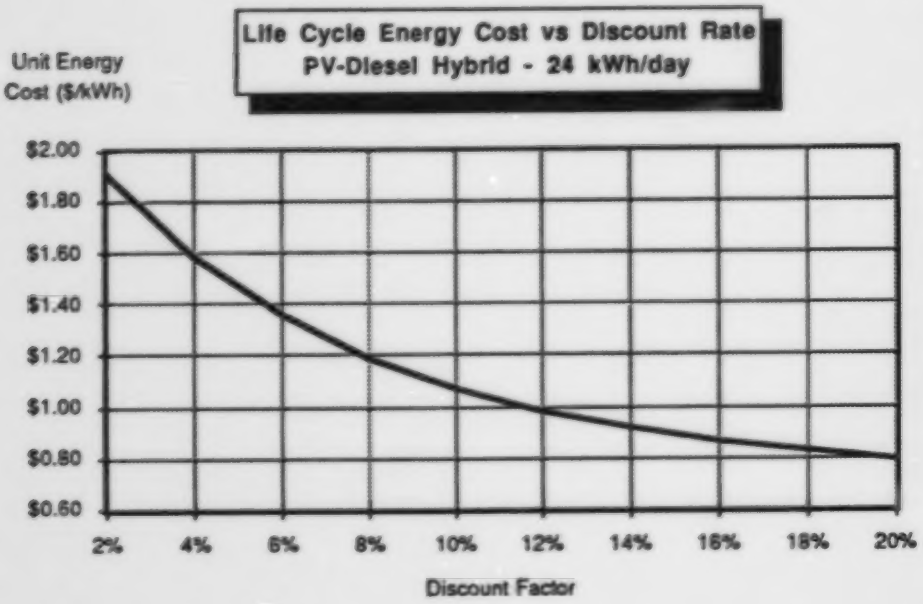


FIGURE 2-25 COST SENSITIVITY TO DISCOUNT FACTOR

Figure 2-26 shows the sensitivity of the life cycle energy costs to inflation of fuel costs. The present analysis uses an 8% rate, which is slightly above the general inflation rate. As expected, the cost of hybrid system energy increases with increased fuel inflation. Once again, the hybrid will be much less sensitive overall than a prime diesel system in which fuel accounts for half of the life cycle costs.

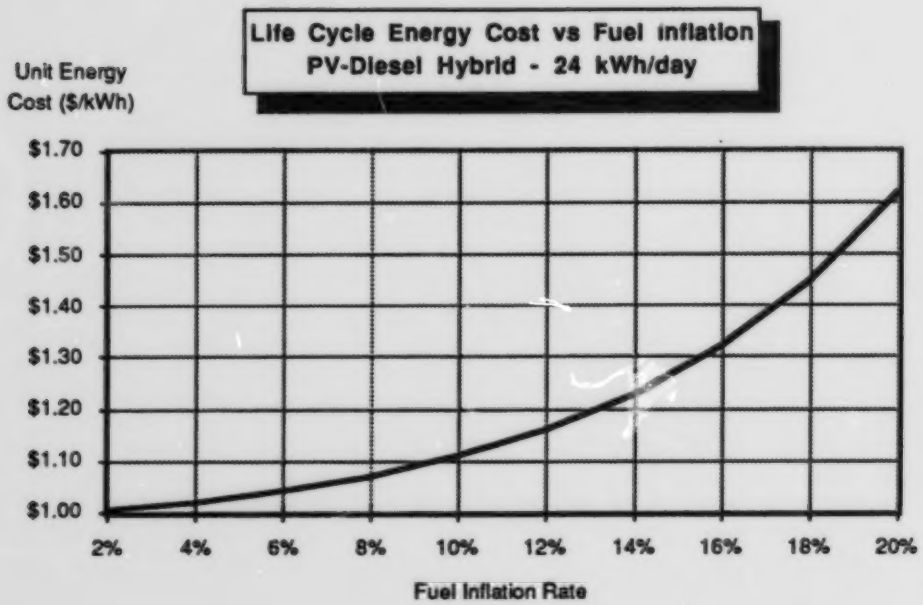


FIGURE 2-26 COST SENSITIVITY TO FUEL INFLATION

Figure 2-27 shows the sensitivity of the life cycle energy costs to inflation of non-fuel costs. The present analysis uses an 6% rate. As expected, the cost of hybrid system energy increases with increased inflation. Note that the system is much more sensitive to general (non-fuel) inflation. This is because of the large battery replacement component as well as the ongoing annual maintenance.

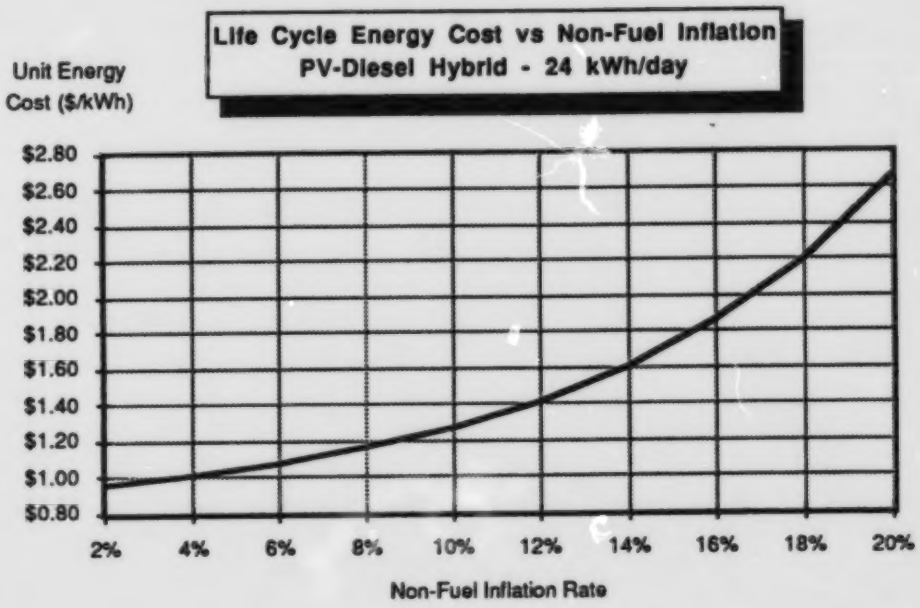


FIGURE 2-27 COST SENSITIVITY TO NON-FUEL INFLATION

2.8. Standalone PV System

A standalone PV system provides a good comparison with the hybrid system in terms of capital costs, operating costs and overall life cycle costs.

The advantages of a standalone PV system are inherent in its simplicity. With no moving parts, the need for maintenance is reduced to almost nothing, and with a free fuel source (assuming no trees or buildings grow to shade the array during its life time), there are no recurring fuel costs subject to inflations and the whims of international politics.

The primary disadvantage of a standalone solar system lies in its sizing. In order to supply a continuous load, a solar system must contain enough battery to accept the solar energy that is available, and supply energy to the load during the periods when the sun is not shining. The size of its battery is typically between five and fifteen days, depending on the reliability required. An even more important factor is the annual solar insolation available. Since the system must support the load, even in the months with the worst solar insolation, the entire system must be sized for the worst case. This results in a dramatic oversizing for the rest of the year, meaning that as much as 70% of the available energy in peak months must be regulated. This inefficiency translates directly into added capital costs in a PV system, and dramatically affects the long term analysis, as expressed by life cycle energy costs.

IPC SOLCAD® sizing software was used to size a standalone system to meet the same load as the hybrid system. SOLCAD® uses a statistical model which analyzes the effect of insolation variability on system behavior to derive an accurate estimate of system performance. Availability is determined by "Loss-of-Load-Probability), or the probability that the system will be forced to shed its load due to low battery state of charge. A high reliability system generally has an availability of more than 99.9%, corresponding to less than 8 hours of down time per year. This level of reliability is achieved as a result of oversizing both the battery and the array, to allow for long periods of low insolation and a few days with high insolation for recharging, and is often not achievable at all in certain areas with low insolation values. This availability level is critical for certain applications, such as microwave backbone link, but is generally too high for remote community

applications. The comparison system was designed for a medium availability in order to avoid loading the system with too much safety margin, and thus increasing its overall cost.

Figure 2-28 shows the insolation summary for an array tilted for maximizing the worst case insolation. In this case, the tilt is 65 degrees, compared with 50 degrees for the hybrid system.

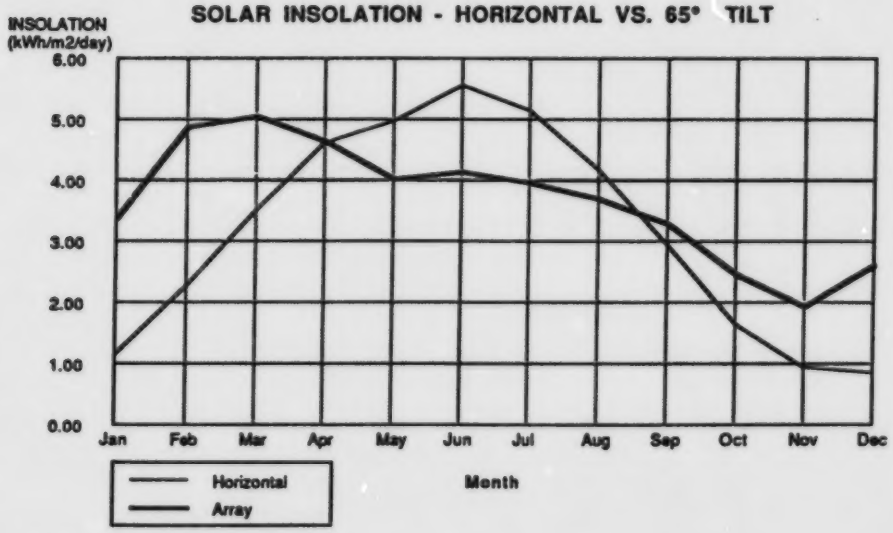
Figure 2-29 shows the system design summary and system availability analysis for this system. The system consists of 800 PV modules, a 20,000 Ah, 120 VDC battery providing 7 days of autonomy, an inverter, standard control electronics, and system shelter. Total estimated cost is $500,000, including shipping, installation and engineering/project management (typically ≈10%), with annual maintenance costs of $500.

Figure 2-30 shows the life cycle cost summary, and Figure 2-31 provides the same information in graph form. Note that the life cycle energy cost for the standalone solar system is more than double the value for the baseline hybrid system. In a climate more favorable to standalone solar, this cost differential might be reduced somewhat, but the need for reliability and the variability of solar insolation almost always render the standalone system costs higher for moderate loads. As the loads get smaller, the balance-of-system (BOS) needed for a hybrid system take in increasing proportion of the cost, and standalone solar gets more and more economic. A power requirement of 5 kWh/day is often quoted as the transition point between standalone and hybrid systems, although the exact value is dependent on climate, load variations, access to site, and other factors.

SOLCAD® TILT CORRECTION MODULE

CITY: Moosonee **STATE:** Ontario **COUNTRY:** Canada
LATITUDE: 52°00' N **LONGITUDE:** 81°00' W **TILT:** 65° South facing
COMMENTS: From Canada Climate Normals

MONTH	HORIZONTAL INSOLATION (kWh/m2/day)	TILT FACTOR	ARRAY INSOLATION (kWh/m2/day)
Jan	1.16	2.91	3.37
Feb	2.25	2.17	4.89
Mar	3.49	1.45	5.07
Apr	4.62	1.00	4.64
May	4.98	0.81	4.02
Jun	5.57	0.75	4.16
Jul	5.14	0.77	3.97
Aug	4.18	0.89	3.71
Sep	2.93	1.12	3.29
Oct	1.66	1.48	2.46
Nov	0.94	2.06	1.93
Dec	0.86	3.05	2.62
		WORST CASE:	1.93
		AVERAGE:	3.68



INTEGRATED POWER CORPORATION
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FIGURE 2-28 INSOLATION SUMMARY FOR STANDALONE PV SYSTEM

SOLCAD® SYSTEM SUMMARY REPORT

CITY: Moosonee **STATE:** Ontario **COUNTRY:** Canada **LATITUDE:** 52°00' N
Array is 560 modules of 3.00 Amps each @ 48 Volts, tilted @ 65° South facing
Rated Battery storage is 10.21 days (to 80 % DOD) or 7500 amp-hours.
COMMENTS : From Canada Climate Normals

SYSTEM AVAILABILITY ANALYSIS

MONTH	INSOL kWh/m2/d	CLEAR NESS	SIGMA RATIO	AVG TEMP °C	ARRAY OUTPUT Ah/d	LOAD Ah/d	ARRAY \LOAD RATIO	ADJ BATT STOR	LOLP
Jan	3.37	0.52	0.58	0	1274.2	587.50	2.17	6752.9	0.25 %
Feb	4.89	0.60	0.38	5	1847.3	587.50	3.14	6961.4	0.00 % *
Mar	5.07	0.58	0.37	10	1915.7	587.50	3.26	7141.6	0.00 % *
Apr	4.64	0.54	0.42	15	1752.5	587.50	2.98	7293.5	0.15 %
May	4.02	0.47	0.44	20	1517.7	587.50	2.58	7417.3	0.07 %
Jun	4.16	0.48	0.38	25	1571.4	587.50	2.67	7500.0	0.04 %
Jul	3.97	0.46	0.39	25	1500.3	587.50	2.55	7500.0	0.05 %
Aug	3.71	0.45	0.48	20	1402.8	587.50	2.39	7417.3	0.11 %
Sep	3.29	0.42	0.58	15	1242.8	587.50	2.11	7293.5	0.28 %
Oct	2.46	0.38	0.73	10	930.7	587.50	1.58	7141.6	0.41 %
Nov	1.93	0.37	0.83	5	731.3	587.50	1.24	6961.4	1.79 %
Dec	2.62	0.47	0.65	0	990.7	587.50	1.69	6752.9	0.19 %

Annual Availability: 99.72 %

BATTERY STATE OF CHARGE REPORT

BSOC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
90 - 100 %	0.49	-	-	0.45	0.55	0.57	0.56	0.53	0.49	0.51	0.36	0.57
80 - 90 %	0.33	-	-	0.45	0.35	0.36	0.35	0.34	0.33	0.22	0.19	0.22
70 - 80 %	0.09	-	-	0.04	0.05	0.04	0.05	0.06	0.09	0.12	0.14	0.10
60 - 70 %	0.04	-	-	0.04	0.02	0.02	0.02	0.03	0.04	0.07	0.10	0.05
50 - 60 %	0.03	-	-	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.08	0.03
40 - 50 %	0.01	-	-	0.01	0.00	0.00	0.00	0.01	0.01	0.02	0.06	0.01
30 - 40 %	0.01	-	-	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.04	0.01
20 - 30 %	0.00	-	-	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.04	0.00
10 - 20 %	0.00	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0 - 10 %	0.00	*N/A	*N/A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

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FIGURE 2-29 STANDALONE PV SIZING & RELIABILITY SUMMARY

LIFE CYCLE COST ANALYSIS *© IPC 1989*

Description	24 kWh/day Standalone PV System
Analysis Period	25 yrs

Components	$364,800
Shipping	$6,000
Installation	$16,000
Distribution	$0
Project Management	$10,000
Total Capital	$396,800
% Financed	0%
Amount Financed	$0
Loan Term	25 yrs
Loan Interest	10.0%
Loan Payments	$0
Energy Produced	24 kWh/day

Discount Rate	10.0%
Fuel Escalation	8.0%
Fuel Esc Ratio	0.982
Non-Fuel Escalation	6.0%
Non-Fuel Esc Ratio	0.964
Fuel Use	0
Fuel Cost per Litre	$0.60
Recurring Fuel	$0
Recurring Non-Fuel	$500

Non-Recurring Item	Amount	Year
Battery	$95,296	13

Item	Amount	Year	Factor	LCC
Capital	$396,800	0	1.000	$396,800
Loan Payment	$0	all	25.000	$0
Recurring Fuel	$0	all	19.867	$0
Recurring Non-Fuel	$500	all	16.003	$8,001
Battery	$95,296	13	0.618	$58,877
	$0	0	1.000	$0
	$0	0	1.000	$0
	$0	0	1.000	$0
	$0	0	1.000	$0

Total LCC	$463,678
Total Energy	219,000
Unit Cost	$2.117

FIGURE 2-30 STANDALONE PV LIFE CYCLE COST SUMMARY

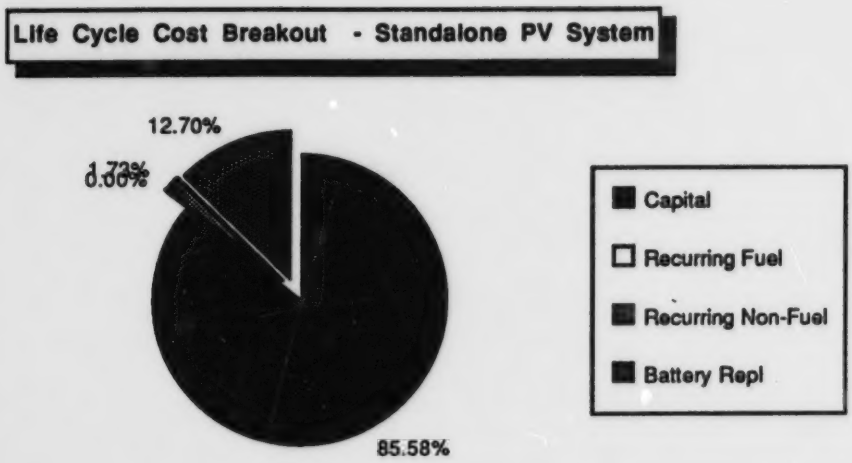

FIGURE 2-31 STANDALONE PV LIFE CYCLE COST BREAKOUT

2.9. Prime Diesel Generator

As a final comparison, this section provides a simplified analysis of a system incorporating a prime diesel generator to supply the load. Diesel generators are the single most predominant technology used to supply power to remote areas today.

Their advantages include high power density (lots of power in a small package), low installed cost, and worldwide familiarity. Disadvantages include a number of issues that are opposite to PV systems - cost of fuel, maintenance requirements, pollution, noise - and one that is common - oversizing. The oversizing is necessary to ensure that the generators have enough capacity to supply peak loads which occur only a few times during the year. This oversizing is only possible by selecting a generator which has sufficient capacity to meet the short term peaks. Typical load factors on a prime diesel system are 17 to 20%. Since it is harmful to the engine to run it at such a low load for extended periods, a supplementary load must be placed on the output to maintain the load to at least 40% of capacity. This "dummy" loading has the effect of cutting the net fuel efficiency in half. Another disadvantage of a prime diesel is that the engine must run continuously in order to supply power. Since maintenance costs are based on operating hours, life cycle costs are directly affected.

The prime diesel system was sized in accordance with standard practice, which dictates using oversized diesels. In systems with loads of 50 kW and above, more advanced control techniques incorporating staging of different sized engines can be used, but in the current example, a simple redundant system is the only real choice.

The prime diesel system consists of redundant generators, each rated to approximately twice the predicted peak load, or approximately 10 kW each. Only one generator is on at any given time, but the two are controlled so that they share hours equally. The system includes a load bank to keep the generator loading above 40% in order to prevent coking and other problems associated with low loading of diesel generators. While there are more advanced ways of running generators in larger systems, including sequencing different size units to keep the

loading higher during different parts of the day, these techniques typically do no apply to installations as small as this.

Maintenance includes oil changes at 750 hr intervals (two month intervals if both engines are used), decarbonizations at 1500 hr intervals (done every other oil change on both engines), and overhauls at 6000 hrs (performed once every 18 months). Typical lifetime for a prime power diesel engine is 20,000 to 40,000 hours. For this simple analysis, assume each engine will last eight years with 50% duty cycle (equivalent to 35,000 hours).

Figure 2-33 shows the life cycle cost summary, and Figure 2-34 provides the same information in graph form. Note that virtually all of the life cycle cost is in fuel and maintenance, compared to the PV system which is heavily loaded towards capital cost. The hybrid system lies somewhere in between (ref Fig 2-13).

The life cycle energy cost of the diesel system is nearly twice that of the baseline hybrid system, and while hybrid system costs will be going down due to technology improvements in PV cells and batteries, diesel costs have nowhere to go but up.

LIFE CYCLE COST ANALYSIS © IPC 1989

Description	24 kWh/day Diesel Generator
Analysis Period	25 yrs

Components	$28,000
Shipping	$1,000
Installation	$2,500
Distribution	$0
Project Management	$3,000
Total Capital	$34,500
% Financed	0%
Amount Financed	$0
Loan Term	25 yrs
Loan Interest	10.0%
Loan Payments	$0
Energy Produced	24 kWh/day

Discount Rate	10.0%
Fuel Escalation	8.0%
Fuel Esc Ratio	0.982
Non-Fuel Escalation	6.0%
Non-Fuel Esc Ratio	0.964
Fuel Use	15,768
Fuel Cost per Litre	$0.60
Recurring Fuel	$9,461
Recurring Non-Fuel	$9,031

Non-Recurring Item	Amount	Year
Gensets	$24,000	8
Gensets	$24,000	16

Item	Amount	Year	Factor	LCC
Capital	$34,500	0	1.000	$34,500
Loan Payment	$0	all	25.000	$0
Recurring Fuel	$9,461	all	19.867	$187,961
Recurring Non-Fuel	$9,031	all	16.003	$144,521
Gensets	$24,000	8	0.744	$17,845
Gensets	$24,000	16	0.553	$13,269
0	$0	0	1.000	$0
0	$0	0	1.000	$0
0	$0	0	1.000	$0

Total LCC	$398,095
Total Energy	219,000
Unit Cost	$1.818

FIGURE 2-32 SMALL PRIME DIESEL LIFE CYCLE COST SUMMARY

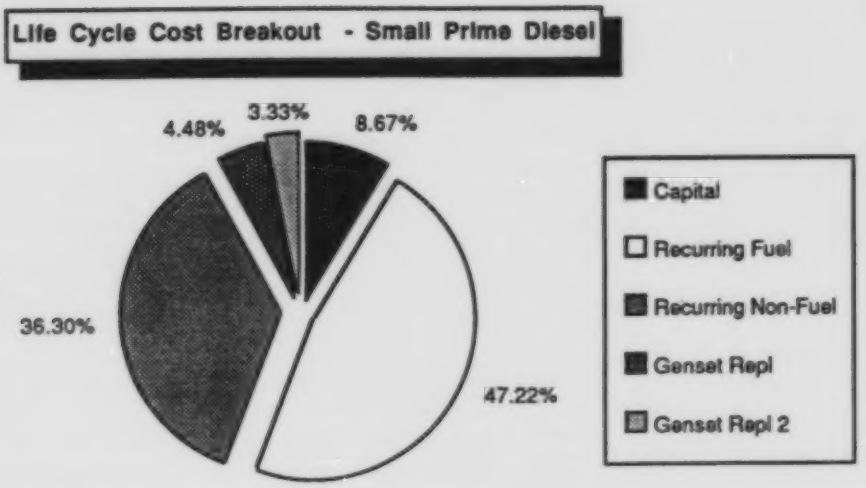

FIGURE 2-33 SMALL PRIME DIESEL LIFE CYCLE COST BREAKOUT

3. Battery Modeling

3.1. Battery Types

In many ways, batteries are the heart of a hybrid system, and careful consideration must be given to the selection and proper care of the batteries. The capacity requirements of hybrid systems lend themselves to lead acid batteries, although ni-cads might also be used in some applications and future technologies such as nickel-hydrogen and zinc-bromide might eventually find use in these applications. This report covers only commercially available lead acid batteries. Specific requirements for hybrid systems include:

- The batteries should be able to tolerate frequent cycles to moderate depths of discharge. This means that the batteries must be similar to traction batteries, which typically use lead-antimony alloys rather than lead calcium or pure lead as the positive plate material. The need for cycling also lends itself to a tubular positive plate construction for added strength, rather than the more standard pasted plate types used in float batteries. Figure 3-1 shows cycle life as a function of depth of discharge for a typical battery.

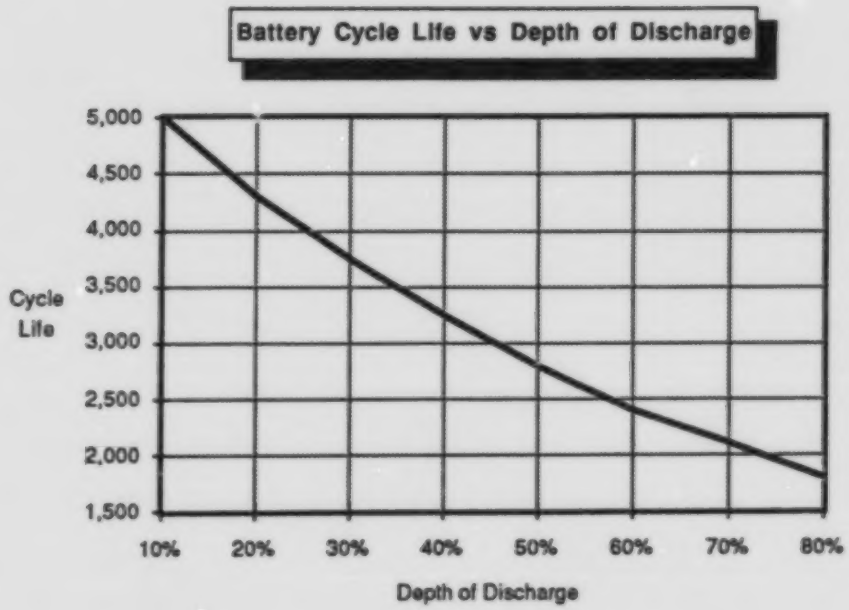

FIGURE 3-1 TYPICAL BATTERY CYCLE LIFE

- The batteries must be capable of widely varying rates of charge and discharge ranging from C/5 to C/72 for charging and C/3 to C/400 for discharging. This affects both the internal and external structure of the batteries. Figure 3-2 illustrates the relationship between capacity and discharge rate for a typical cycling battery.

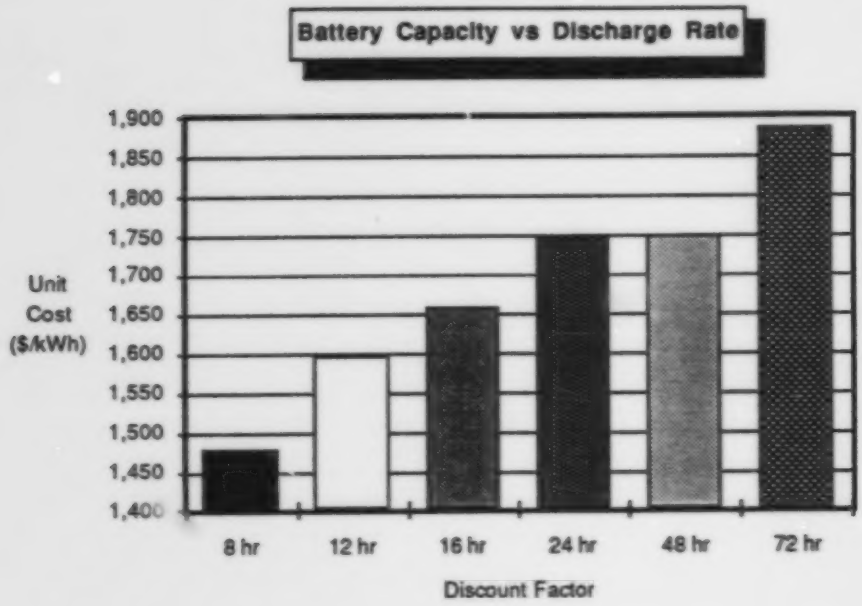

FIGURE 3-2 TYPICAL BATTERY CAPACITY VS DISCHARGE RATE

- The battery should be low maintenance. Ideally, sealed, or "valve regulated" batteries would be best. If flooded batteries are used, they should have a low gassing rate, reserve electrolyte space, and high efficiency. These characteristics are more typical of lead-calcium float batteries rather than lead antimony traction batteries, which puts this requirement in direct conflict with the first requirement above.

- The batteries should be able to operate in temperature extremes, both hot and cold. While many of the requirements for remote communities and telecommunications sites in Canada are in arctic environments, there are a great many applications for hybrids in developing countries

located much closer to the equator. In a hybrid system in a cold environment, the waste heat from the diesel generator can be used to keep the batteries warm, making the problem of cold weather operation of hybrid batteries much less severe than standalone PV systems or other applications where there is no readily available source of waste heat. The problem of keeping batteries cool in hot climates without resorting to energy-expensive techniques such as air conditioning is much more difficult, so the high temperature operation of a battery is generally the driving design factor.

- Finally, the batteries should have a long lifetime. Since the lifetime of the system is approximately 25 years, the batteries should ideally be able to match this lifetime. While some float batteries maintained under ideal conditions (i.e. at steady 25°C temperatures with infrequent discharges and prompt recharging) approach this ideal lifetime, it is impractical to assume that any cycling battery will give much more than half of this tenure. If the battery is cycled very frequently, then eight to nine years is the best that can be expected. As a comparison, high antimony traction batteries on daily discharges rarely exceed five years calendar life, and require tremendous amounts of maintenance (due to increased gas evolution) at the end of this life.

The question of sealed versus flooded construction is very important today in any industry that uses rechargeable lead acid batteries, especially with sealed technologies making tremendous strides towards penetrating the market in float batteries, and low power cycling batteries such as home appliances and hand tools.

There seems little doubt that, over the next ten years or so, sealed batteries will become dominant in virtually all applications, however, for the moment, flooded batteries remain the prime choice for hybrid applications. Flooded batteries currently have better cycling ability than sealed counterparts. In addition, flooded batteries can generally accept a higher charge rate than sealed batteries, meaning that larger generators can be used with consequent reduction in operating time and maintenance costs.

Finally, flooded batteries are more suited to hot environments than sealed batteries. If excess electrolyte is lost in a flooded battery due to diffusion through the case or some similar mechanism, it can simply be replaced, whereas the loss in a sealed battery is irreplaceable. In the case of a "starved electrolyte" type of sealed battery, the lost water means a consequent loss in capacity. In a gelled electrolyte, drying out of the gel can cause it to pull away from the plates, leading to voltage spikes and improper charging. The sensitivity of sealed batteries is also apparent when subjected to controlled overcharging, such as is typically done to flooded batteries to "equalize" the batteries. While sealed batteries are not as prone to drift as flooded batteries, there is still evidence that the cells do not maintain full parity with each other under the types of conditions encountered in hybrid systems. Figure 3-3 shows a voltage versus time curve of a 12 volt bank of sealed cells with two weak cells. Note the four volt drop in capacity when the two cells reached 0% SOC, then a levelling out as the other four cells took over. In order to bring all cells up to full state of charge, a controlled overcharge must be given to the full bank. The penalty with flooded batteries is a slight amount of lost electrolyte, which can readily be replaced. With sealed batteries, this equalization must be done under very controlled conditions, usually with a very low charge rate in order that the gas evolution does not exceed the recombination ability of the battery. While this is not a major problem with a battery that is being recharged from the power grid, it causes excessive run times of the diesel engine in a hybrid system, resulting in wasted fuel and more frequent maintenance requirements.

While this is a very demanding application for a rechargeable battery, there are a number of suitable designs available. In order to study the batteries further, two representative batteries have been chosen - the Exide E31 series flooded lead acid, with low antimony tubular positives and lead calcium pasted negatives, and the Sonnenschein A600 Solar valve-regulated battery with gelled electrolyte, lead calcium tubular positive plates and lead calcium pasted negatives.

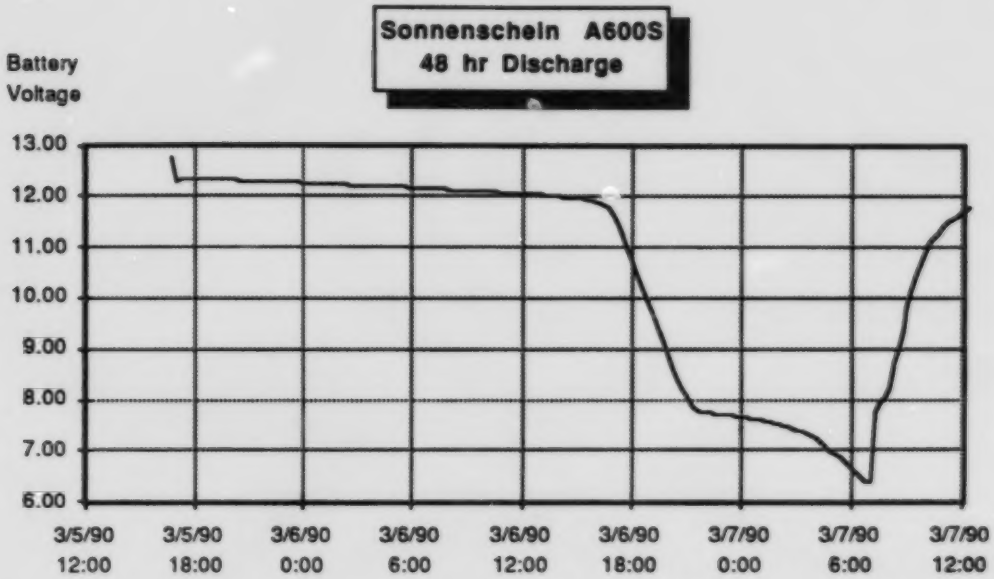

FIGURE 3-3 VOLTAGE VS TIME CURVE

Aside from the gross characteristics of the batteries, it is essential to have a detailed understanding of the behavior of the battery under hybrid system operating conditions. This is important on discharge, because it allows the system designer to have direct control over the depth of discharge for each cycle. It is even more important on recharge, because it allows the designer to fine-tune a recharge algorithm that is optimized for both the battery (in terms of maximized efficiency) and the system (in terms of minimized run time of the diesel).

The two batteries mentioned above have been extensively studied by the Electrochemical Science and Technology Center of the University of Ottawa in Ottawa, Ontario, Canada under contract to Westinghouse Canada. (The same types of batteries were also subjected to a number of "check cycles" at IPC in Rockville, Maryland.) During this period, the batteries were subjected to continuous cycling at various rates. The discharge and recharge curves were recorded on a computer and used to formulate a specific mathematical model of the battery, which is discussed in the two sections below. In addition, knowledge of battery state of charge allows the development of even more advanced algorithms for control of the system. For instance, if the generator is set to come on at 25%

SOC and the BSOC is currently 40%, the control system could decide to turn of the generator anyway, based on a predicted upcoming load peak "learned" from previous experience. This would put the battery in a better position to handle the high loads without causing excessively low voltages.

There are a number of different ways to determine battery state of charge. The most obvious is to simply count the number of amp-hours (or kWh) into and out of the battery. The problem with this is that the battery has different efficiencies at different state of charge and at different charge rates. Under very controlled circumstances such as a UPS system with a single discharge followed by an immediate full recharge, amp-hour counting could conceivably work properly. In a hybrid system however, with continuous discharging interspersed with occasional partial and full recharges (at rates ranging from C/8 to C/100), the long term result is that the predicted SOC would drift farther and farther away, making it next to useless as a control measure.

A second way to estimate battery state of charge is to simply assign different voltages to represent different state of charge. This is fine for a controlled situation, and it does not suffer from "drift" as in amp-hour counting, but is has a flaw in that the voltage versus state of charge relationship changes with differing charge and discharge rates. For instance, a battery voltage of 1.95 volts per cell at C/5 discharge rate may represent 80% SOC, whereas at C/72 it may represent only 30% SOC.

For these reasons, the decision was made to use a model which expresses battery state of charge as a function of the battery voltage and discharge rate. This model also needs to be corrected for battery temperature, but this is a relatively well understood process, so it has been left out of the model equations in the sections below, in order to simplify them.

Figure 3-4 shows a typical voltage versus time curve for a battery that is being discharged and recharged using a constant current. Note that the discharge is mostly linear until late in the sequence, while the recharge is linear for a while, rises to a certain point, then tapers off to a plateau. For convenience, the mathematical model developed above was divided into three regions - linear discharge, pre-gassing charge, and post gassing charge. The non-linear part of

the discharge was ignored since the hybrid will never be operating under those conditions. Section 3.2 discusses the discharge region of the model, and Section 3.3 discusses the two recharge regions.

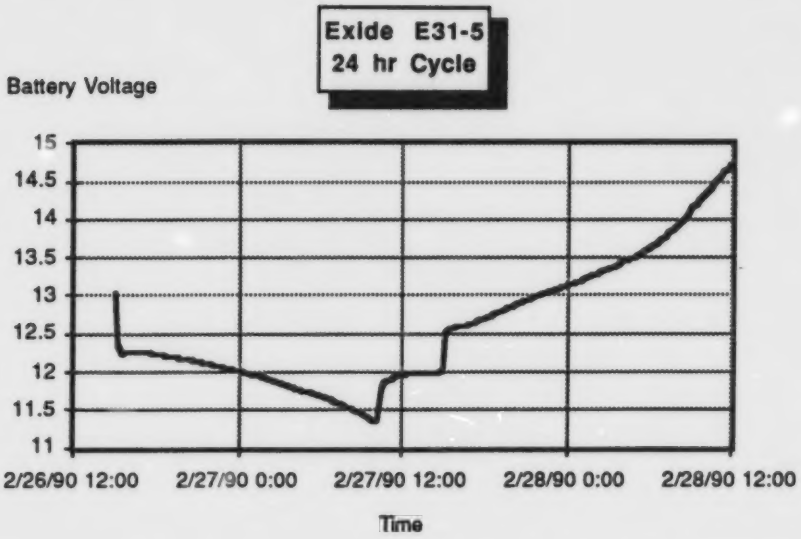

FIGURE 3-4 TYPICAL BATTERY DISCHARGE/RECHARGE CURVE

List of Symbols used in the model:

$C/5$: Typical discharge/recharge rate - one fifth of rated 24 hour battery capacity
Jd : Discharge rate (in hours) - Jd for C/5 = 5
Jc : Charge rate (in hours)
$V0$: Cell voltage at 0% DOD immediately after discharge begins
$V80$: Cell voltage at 80% DOD
V_c : Cell voltage at any given time
V_{op} : Operating Voltage (V0-V80)
V_g : Gassing voltage
V_s : Cell voltage at beginning of charge (after 80% discharge)
V_p : End-of-charge plateau voltage
SOC : Battery State of Charge
SOC_g : SOC at Vg

3.2. Discharge Behavior

Figure 3-5 shows voltage versus time curves for the Exide battery under three different rates of discharge - C/5, C/8, and C/24. Line "A" crosses the curves at 0% DOD points (V0), and line "C" crosses the curves at their 80% DOD states. In order to keep the efficiency calculation orderly, the battery is assumed to have a discharge efficiency of 100%. This is borne out by the observed fact that after a battery is discharged at a high rate to its end voltage, the battery will yield up additional capacity if its discharge rate is lowered (Figure 3-6).

The difference between "A" and "C" represents Vop, and was found to be constant for all three discharge rates, and has a value of 0.233 for the Exide E31s, and 0.217 for the Sonnenschein A600s.

The equation for line "C" is

$$V_{80}(J_d) = [\, J_d \,/\, (a+b*J_d^2) \,] + c \qquad \text{Eq.3.1}$$

where a = 210 (E31) or 300 (A600),
b = 0.57 (E31) or 0.55 (A600), and
c = 1.817 for both batteries

The constant "c" represents a non-linear correction factor added to extend the results to C/72 rates, and were selected using a computer model which simulates the results of the experimental results. This allows an equation for state of charge as a function of battery voltage and discharge rate to be expressed as follows:

$$SOC(V_c,J_d) = [(\, V_c - V_{80} \,) / V_{op} \,] + 0.20 \qquad \text{Eq.3.2}$$

Figure 3-6 shows this equation superimposed onto the curves shown in Fig 3.5.

Solving this equation for the E31 at Vc = 1.88 V and Jd = 5 hr and 8 hr gives

SOC(1.88V,C/5) = 0.42 or 42% SOC
SOC(1.88V,C/8) = 0.37 or 37% SOC

This result is in line with the expected condition that the state of charge at any given voltage will be lower with a longer discharge rate.

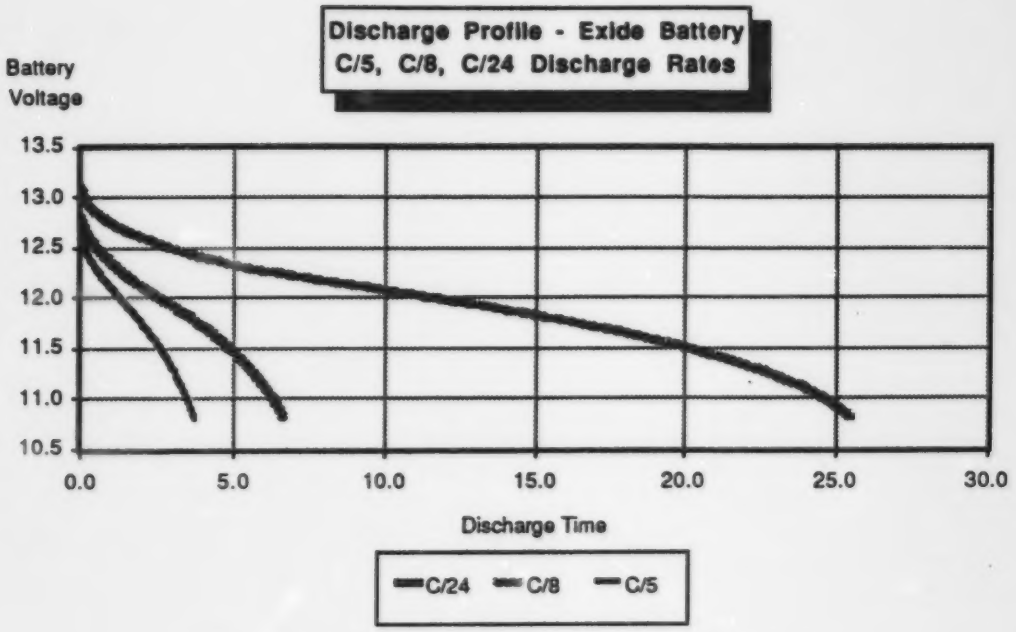

FIGURE 3-5 VOLTAGE VS TIME CURVES-EXIDE

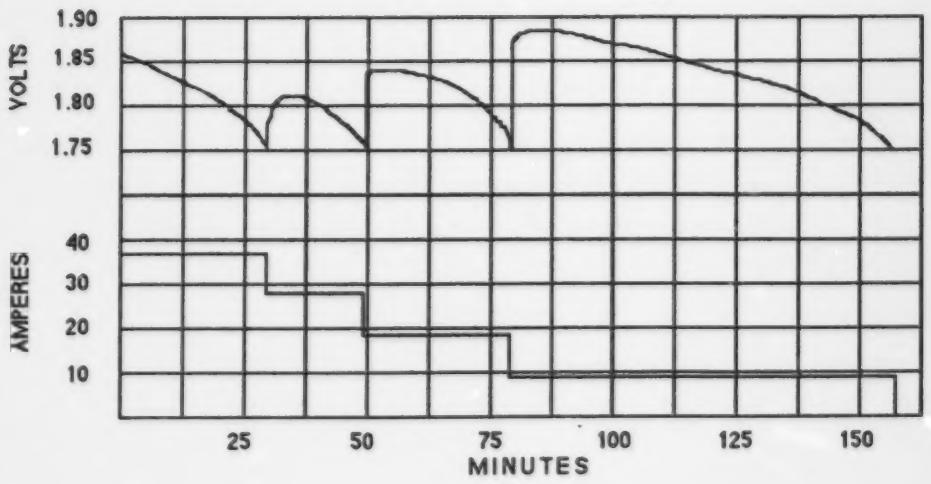

FIGURE 3-6 EFFECT OF DISCHARGE RATES ON CELL VOLTAGE

3.3. Recharge Behavior

The recharge behavior is significantly more complicated, therefore, a single equation is not sufficient to fully describe battery behavior. This complexity stems from the fact that lead acid batteries accept charge at high efficiencies (≈100%) up to a certain point. Above this point, some of the energy goes towards creating hydrogen and oxygen gas rather than recharging the battery. As the battery gets closer to full state of charge, the more energy goes into gassing, until finally all of the energy goes into gassing and no more into charging.

For a typical battery, the gassing voltage changes by only 20 to 40 mV per cell over the life of the battery, so using the gassing point offers a method of calculating SOC that is not susceptible to aging.

The first step is to define the start of charge voltage, Vs, as a function of charge rate:

$$V_s(J_c) = d + (e \ / J_c) \qquad \text{Eq.3.3}$$

where
d = 2.035 (E31) or 2.10 (A600), and
e = 0.531 (E31) or 0.953 (A600)

The next step is to develop the gassing voltage as a function of the charge rate

$$V_g(J_c) = f + (g \ / J_c) \qquad \text{Eq.3.4}$$

where
f = 2.225 (E31) or 2.210 (A600), and
g = 1.476 (E31) or 1.055 (A600)

The next step is to develop the state of charge at gassing as a function of the charge rate. Since the charge efficiency is essentially 100% up to the gassing point, this was done by simply counting amp-hours back into the battery, and finding a polynomial curve fit back to the data.

$$SOC_g(J_c) = h + [J_c / (k + l * J_c^2)] \qquad \text{Eq.3.5}$$

where

h= 0.77

k = 158, and

l = 0.31

note that this equation is the same for both batteries

Assuming the region between Vs and Vg to be linear, the state of charge in this region is:

$$SOC(V_c,J_c) = [(V_c - V_s)/ (V_g - V_s)]* (SOC_g - 0.2) + 0.20 \qquad \text{Eq.3.6}$$

During a constant current charge above the gassing regime, some of the current goes into gassing and some goes into charging the battery.

$$I_{charge} = I_{batt} + I_{gas} \qquad \text{Eq.3.7}$$

The amount of charge current that goes into charging the battery can be expressed as the logarithmic decaying function:

$$I_{batt} = Icharge * (1 - exp(- (t-tg) / \tau) \qquad \text{Eq.3.8}$$

The voltage follows this same basic relationship, levelling off at a plateau voltage. This end of charge plateau voltage was determined experimentally to be:

$$V_p(J_c) = m + (n / J_c) \qquad \text{Eq.3.9}$$

where

m = 2.53 (E31) or 2.80 (A600), and

n = 0.57 (E31) or 0.64 (A600)

Since the amount of net charge current alone determines the state of charge increase in the battery, the relationship between SOC and charge rate and voltage is linear between the gassing voltage and the plateau voltage:

$$SOC(V_c,J_c) = SOC_g+[(V_c - V_g)/ (V_p - V_g)] * (1-SOC_g) \qquad \text{Eq.3.10}$$

The efficiency of the battery follows the same relationship as the SOC, except the efficiency goes from 100% at the gassing voltage to 0% at the plateau voltage:

$$eff_{charge} = 1 - [(V_c - V_g)/ (V_p - V_g)] \qquad \text{Eq.3.11}$$

4. Control Algorithms

4.1. Discharge Algorithm

The discharge algorithm in a hybrid system has two primary functions - generator starting and load management. Both of these functions should be based on battery SOC.

The generator start level should be based on an analysis of the system behavior. This decision is a tradeoff between cycle life and cycle depth. In a simple cyclic diesel system, this analysis can be done rigorously, with a single value emerging as to the optimum discharge level. However, in a hybrid system there are intermediate cycles due to the recharging by the PV array during sunlight hours. Experience has shown that a level between 25% and 50% SOC is the optimum point, depending on exact system parameters.

Load management consists of two levels - a low voltage alarm warning of impending problems, and a load disconnect where all loads are removed from the system to prevent serious damage from the battery due to excessive discharging. In a standalone PV system, these are very important values, since there is no backup charging. In a hybrid system, both of these conditions assume that the generator has failed to start, so the system is already in an alarm mode.

Typically the load disconnect point is set at 20% SOC. In some cases, a two stage disconnect can be used - low priority loads are disconnected at a level above 20% state of charge, allowing more time before the priority loads are disconnected. There is an added benefit to this procedure. Because the battery has greater capacity at lower discharge rates, reducing the load by 50% will more than double the time remaining before disconnect

The low voltage alarm should be set to a point below the generator start but above the load disconnect point. Incorporated with the low voltage alarm could be a number which indicated estimated time to disconnect at the present discharge rate. This number could be derived by combining the discharge SOC calculation [Equation (Eq) 3.2] with a modified form of Peukert's equation relating battery capacity to discharge rate:

$$Cap(Jd) = p * exp(q*Jd) \qquad \text{Eq.4.1}$$

where p and q need to be determined experimentally

More advanced algorithms are conceivable based on specific project related requirements. For instance, the diesel could be asked to start at 40% SOC but limited to run during the day only. If the SOC falls below 40% at night, the controller would simply set a flag to turn the diesel on when daytime arrived. However, if the SOC fell further during the night, the diesel could be started on an emergency basis before loads were disconnected.

4.2. Recharge Methodologies

There are two main components to the recharge algorithm - solar charging and diesel charging. In a standalone system, solar charging is very important because the system is typically oversized in order to meet the load in worst case insolation. For this reason, large amounts of energy must be regulated every day. In a hybrid system, however, virtually all of the energy produced goes in to the battery, as evidenced by Figure 2-4. For this reason, the majority of the attention in this section will be given to the diesel charging.

The two primary goals in diesel recharging of the battery are to charge the battery in the shortest time possible (in order to keep diesel run time to a minimum), and to charge it using the highest efficiency possible, where this does not interfere with the first goal. A number of different charge scenarios are possible.

In a typical UPS system, the system is designed to recharge the batteries from as low as 20% SOC within one day. The typical method used is to charge the batteries at a constant current until the voltage reaches the "float voltage", then switch to a constant voltage mode and taper the current appropriately (see Figure 4-1). When the battery is fully charged, the rectifier will produce only enough current to maintain the batteries at this "float voltage" plus whatever is being used by the load. The float voltage of a battery is specified by the battery manufacturer based on a goal of maximum efficiency during long term continuous trickle

charging, and has nothing to do with optimizing the recharge time. Batteries subjected to float charging tend to stratify, and need to be subjected to periodic equalization charges in order to keep the batteries in top shape. Float voltages for batteries at 25°C are typically around 2.3 to 2.35 volts per cell.

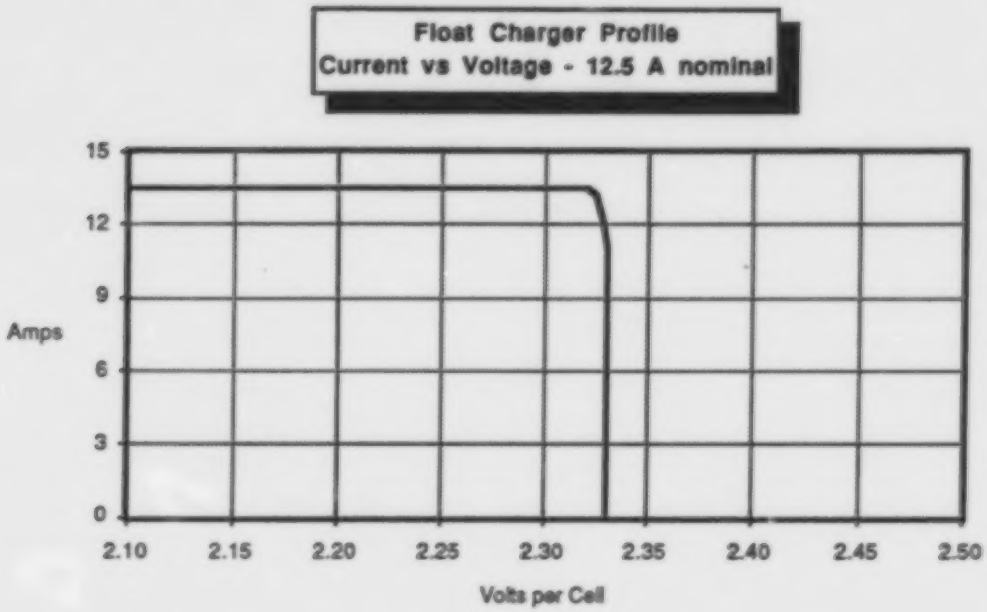

FIGURE 4-1 FLOAT CHARGER - VOLTAGE VS CURRENT PROFILE

A second type of charging is used to provide controlled recharge of traction batteries. In a warehouse, for example, the forklift batteries are sized to provide enough energy for one shift of operation. At the end of that shift, they generally must be recharged within eight hours in order to be used by the third shift. Controllers which recharge these types of batteries provide a very high current,up to a preset voltage level, then taper down gradually as the voltage increases before leveling off at a lower level, typically one third or less of the maximum charge current (see Figure 4-2). This current is then maintained until the batteries are ready to be used again. There is also usually a timer circuit which prevents the batteries from being left on charge for an excessive length of time. The "finishing voltage" in a cyclic recharge can be as high as 2.6 volts per cell. One final difference between this charge methodology and the voltage limited recharge method is that forklift batteries are never recharged with a load attached to them,

while UPS batteries often must maintain the load during recharging, so voltage limits are important.

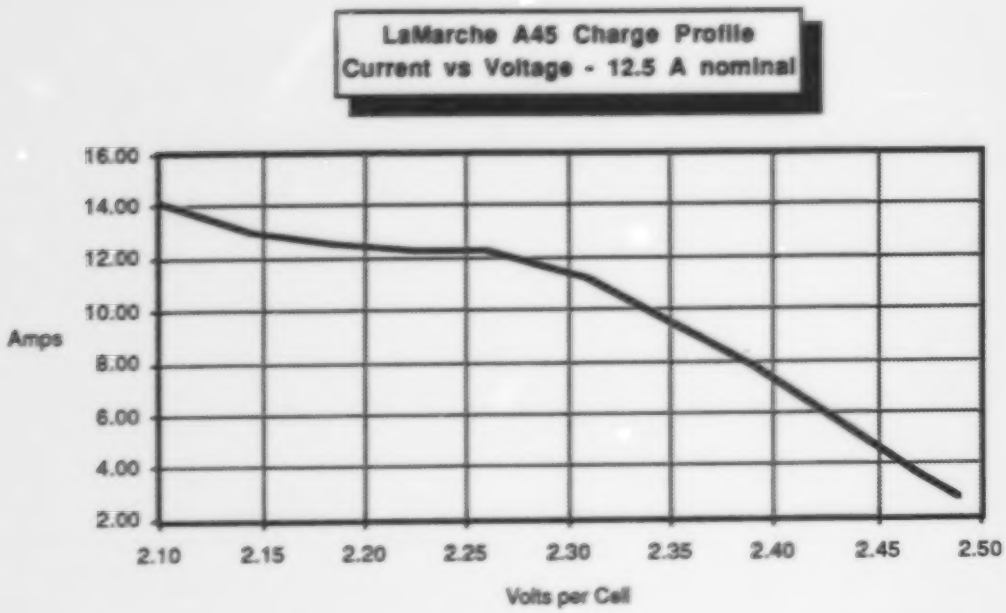

FIGURE 4-2 TRACTION CHARGER - VOLTAGE VS CURRENT PROFILE

A hybrid system requires some combination of the above. Since the diesel generator is used to provide electricity, the time limited traction recharge is more appropriate, however, since the loads remain attached during charging, some sort of voltage control is required. Another reason for limiting the voltage is to limit the currents at high voltages, in order to prevent damage to the battery from excess heating or the potential of explosions from excess gassing.

Because all of the inefficiency (from a amp-hour point of view) is in the post gassing region, it is desirable to limit recharging in a hybrid system to something less than 100% SOC, except during periodic equalizations. Practice has shown that 95% is a good limit - it is high enough to drive most of the sulfate out of the plate, yet is low enough that efficiency does not become a major factor. In order to analyze recharging terminologies it is necessary to provide a level field comparison. The following examples use a 25% to 95% recharge starting with a nominal C/8 current to study differences in charge algorithms.

Figures 4-3 through 4-8 show the recharge characteristics for various types of battery charging schemes, expressed as battery SOC, voltage and charge current vs time curves. These graphs were generated with a computerized model based on the recharge equations in Section 3, using a Exide E31 with a nominal capacity of 100 Ah. The baseline of C/8 as the starting charge rate was chosen as representative of a typical hybrid power system.

Figure 4-3 shows a theoretical constant current recharge. This method is not practical because of temperature, voltage and gassing reasons mentioned above, but it serves as an excellent baseline for further analysis.

Figure 4-4 shows a charge which starts at C/8 but is limited to 2.35 volts per cell. This is representative of a high rate "float" type recharge. Note that it takes significantly longer for the battery to reach higher states of charge.

The third case (Figure 4-5) is the same as the second except the float voltage is extended to 2.45 volts per cell, significantly improving the recharge performance.

The fourth case is a two step recharge, with C/8 rate used up to 2.42 volts per cell, then a single step down to C/24 to finish the charge (Figure 4-6). This case was included because the technology needed to implement this method is relatively simple.

Figures 4-7 and 4-8 use the characteristics of a commercially available traction battery charger - the LaMarche A45 series - to analyze traction type charging. The first A45 curve (Figure 4-7) shows the recharge using the Current-Voltage characteristics as supplied by the factory. It is apparent that this is not a very efficient match to the battery chosen for analysis. The cause of this is that traction batteries have a significantly lower specific gravity than the E31 series Exides, and therefore have lower voltages during charge and discharge. Fortunately, the A45 rectifiers have an adjustment to the taper point via a variable resistor in the control section of the charger. Figure 4-8 shows the effect of adjusting the taper point upwards. This system now looks much more like the 2.45 volt float case above.

As a final charge methodology, a constant current C/24 recharge was plotted to show a typical slow rate recharge (Figure 4-9). Note that the voltages are much lower than in the fast recharges so there is no need to adopt fancy voltage limited chargers, but that the time to 95% SOC is significantly longer than the other methods.

In a comparison of the times needed to bring the battery to various states of charge, the 2.45 V "float" charger and the adjusted A45 charger are very close to being the best choices, while the other three methods take up to 15% longer to reach 95% SOC. The "slow charge" method takes over twice as long as any of the other option.

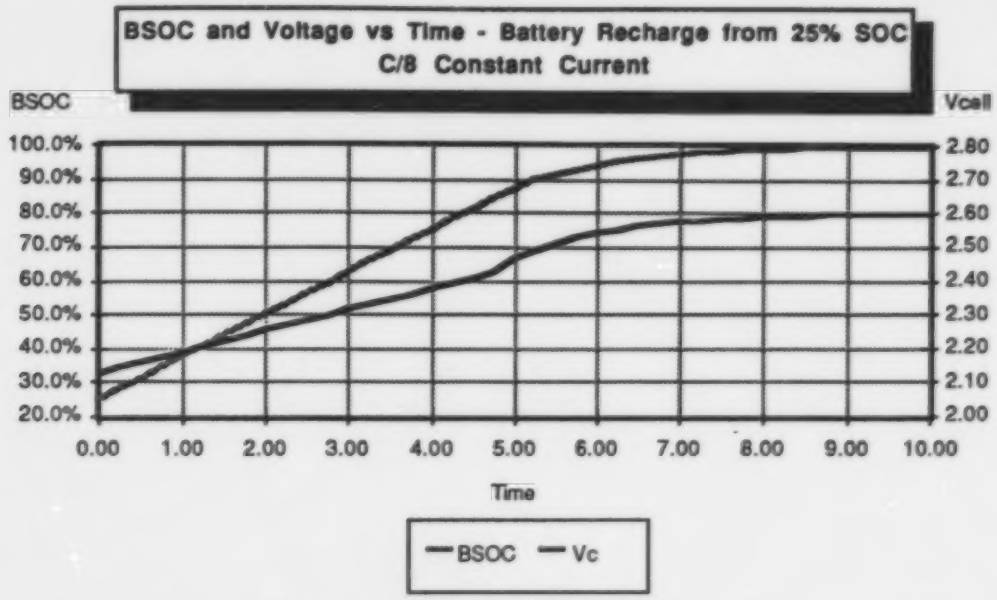

FIGURE 4-3A BSOC & V VS TIME - C/8 CONSTANT CURRENT

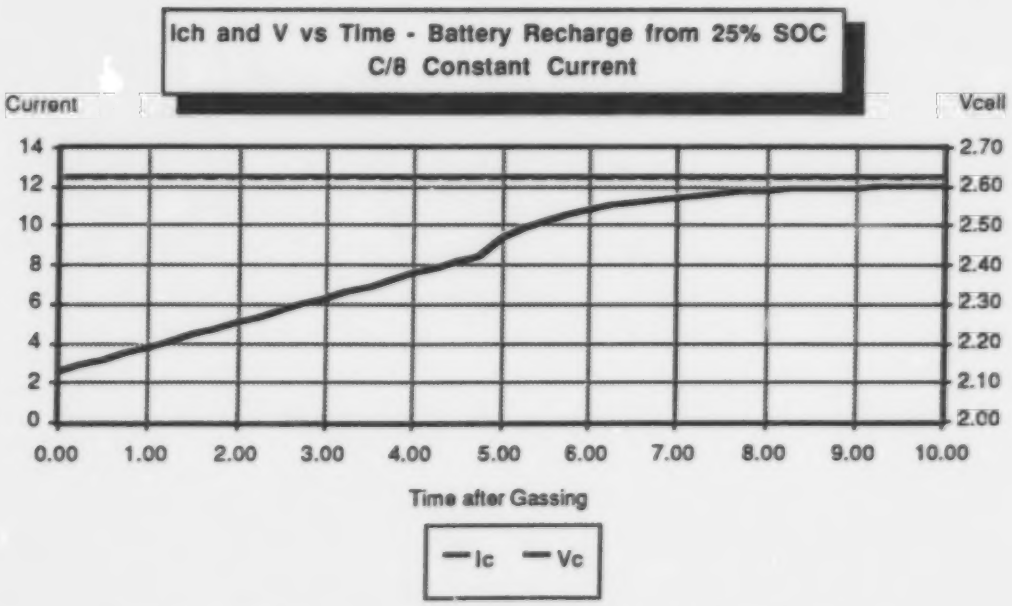

FIGURE 4-3B ICH & V VS TIME - C/8 CONSTANT CURRENT

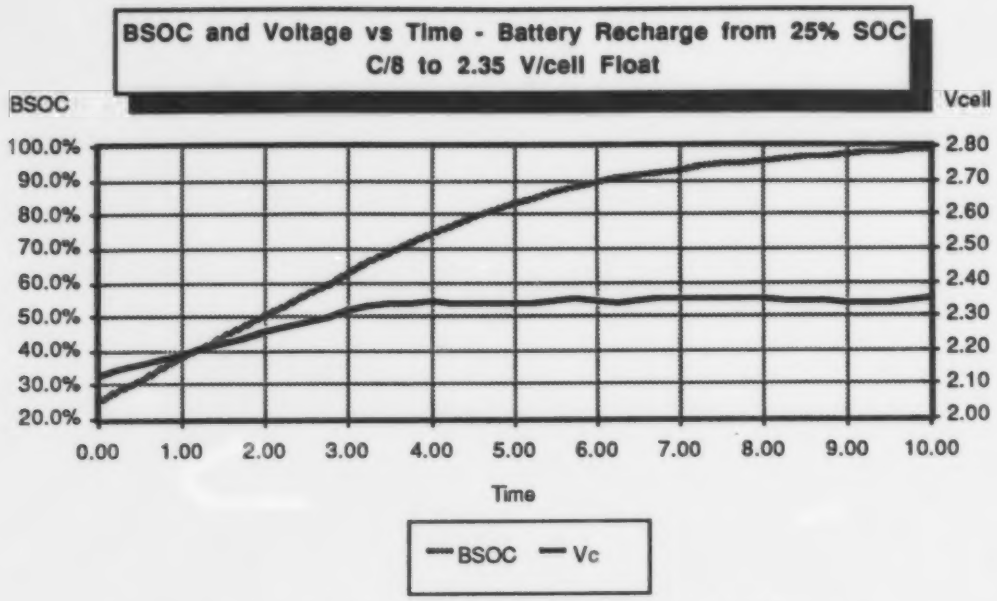

FIGURE 4-4A BSOC & V VS TIME - C/8 TO 2.35 FLOAT

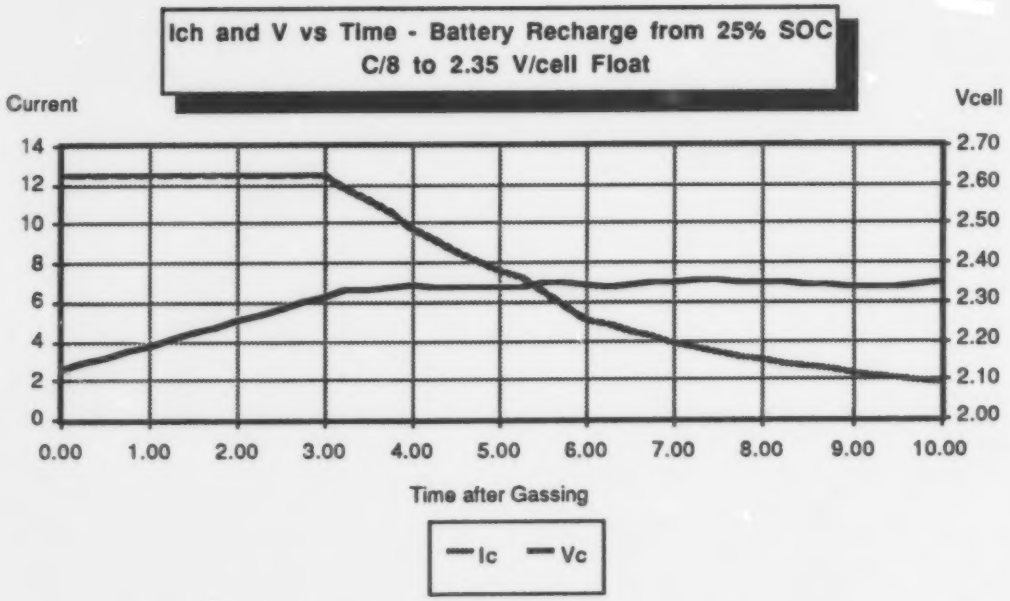

FIGURE 4-4B ICH & V VS TIME - C/8 TO 2.35 FLOAT

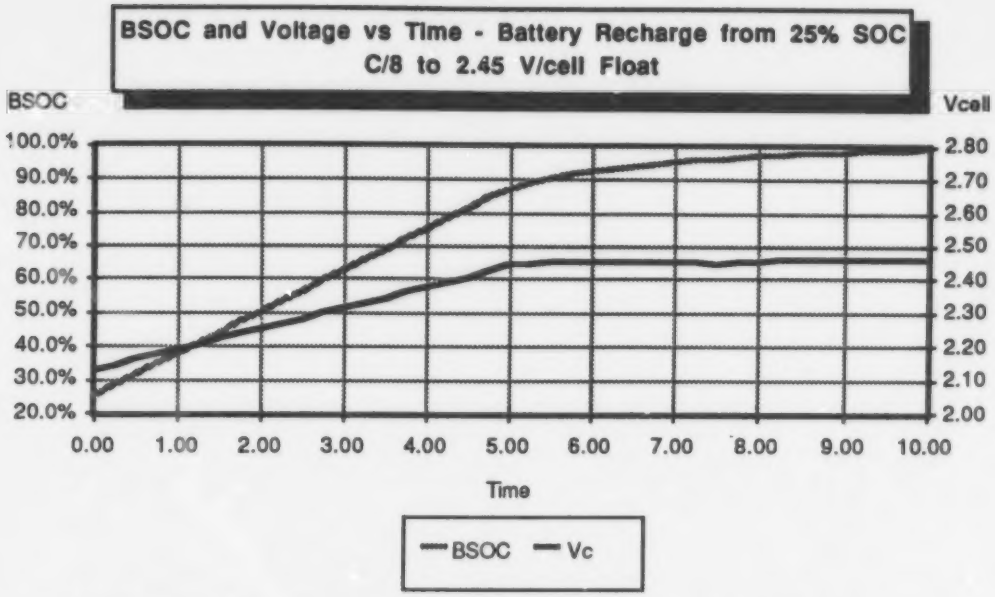

FIGURE 4-5A BSOC & V VS TIME - C/8 TO 2.45 FLOAT

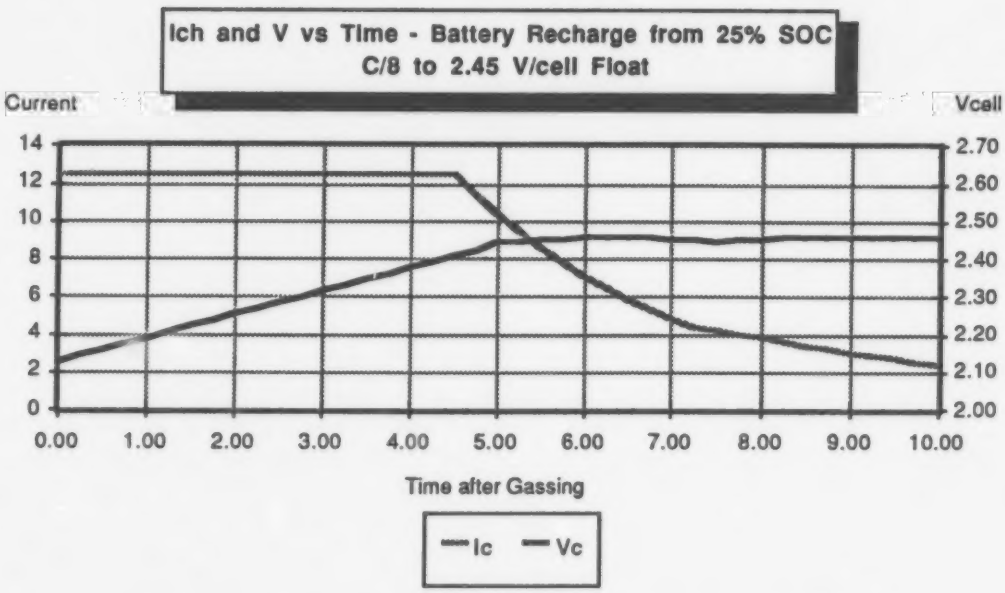

FIGURE 4-5B ICH & V VS TIME - C/8 TO 2.45 FLOAT

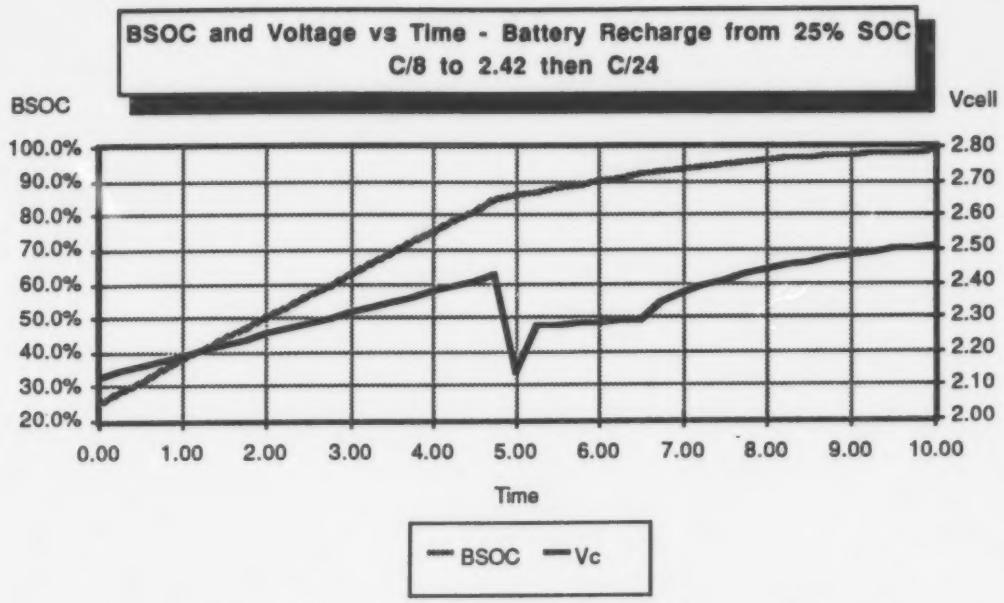

FIGURE 4-6A BSOC & V VS TIME - C/8 TO 2.42 THEN C/24

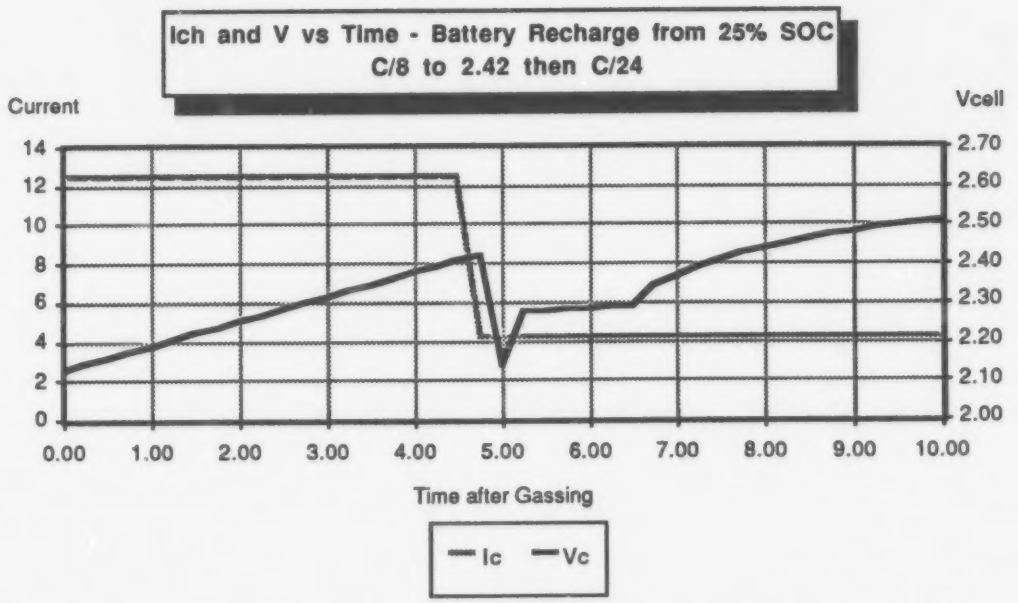

FIGURE 4-6B ICH & V VS TIME - C/8 TO 2.42 THEN C/24

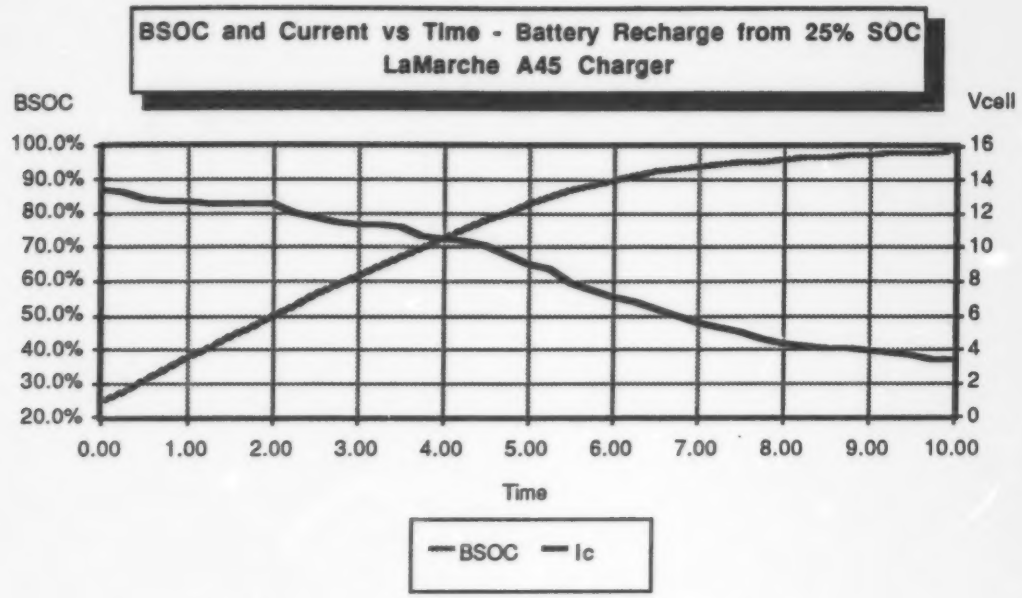

FIGURE 4-7A BSOC & V VS TIME - A45 CHARGER

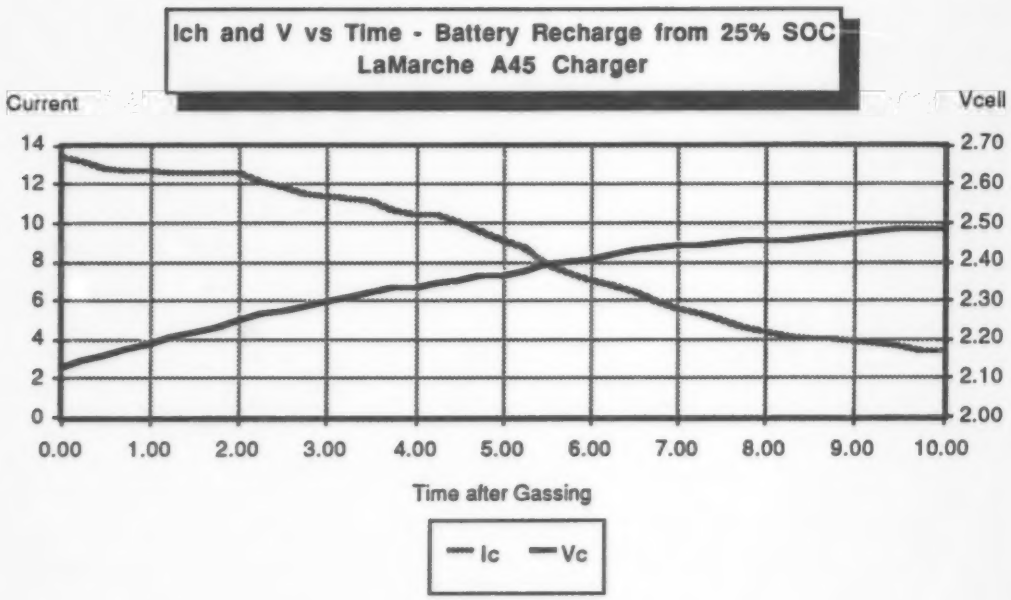

FIGURE 4-7B ICH & V VS TIME - A45 CHARGER

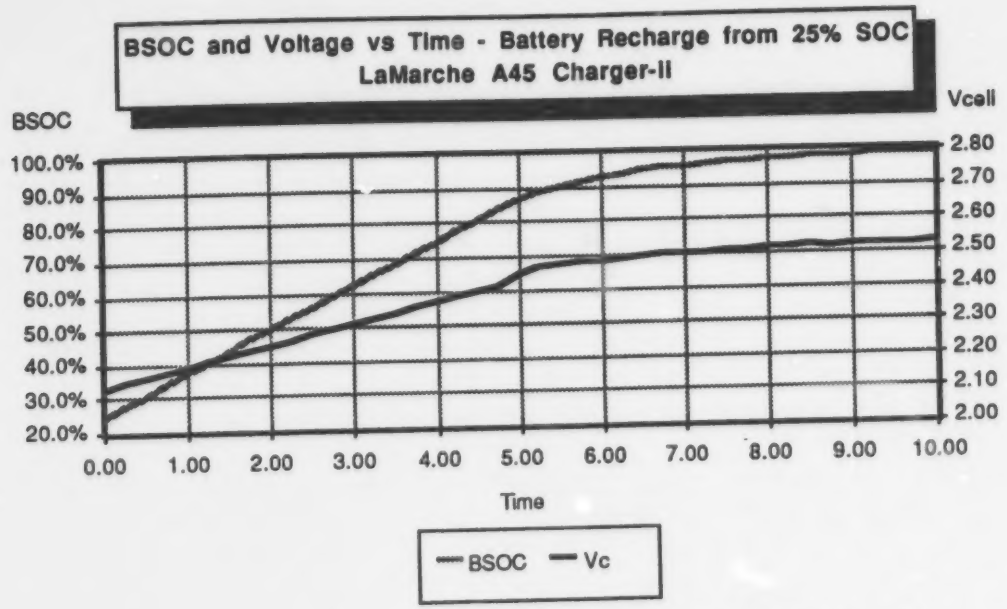

FIGURE 4-8A BSOC & V VS TIME - MODIFIED A45 CHARGER

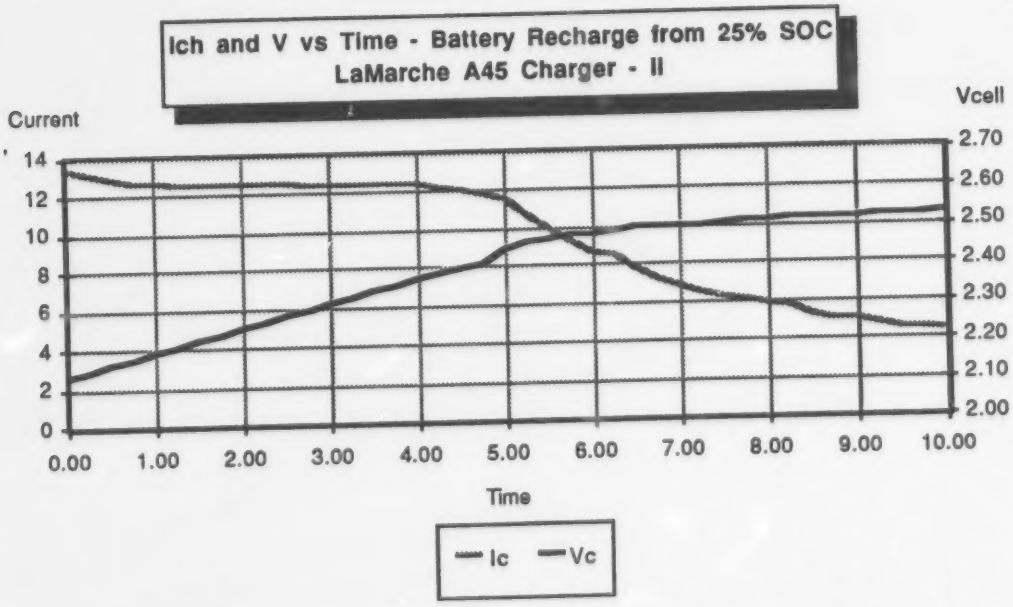

FIGURE 4-8B ICH & V VS TIME - MODIFIED A45 CHARGER

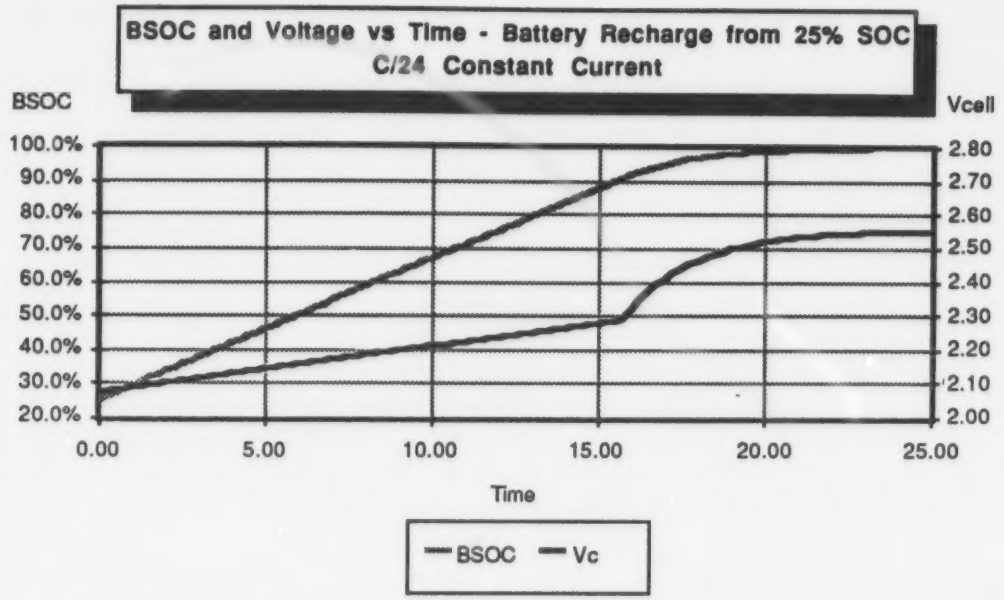

FIGURE 4-9A BSOC & V VS TIME - C/24 CONSTANT CURRENT

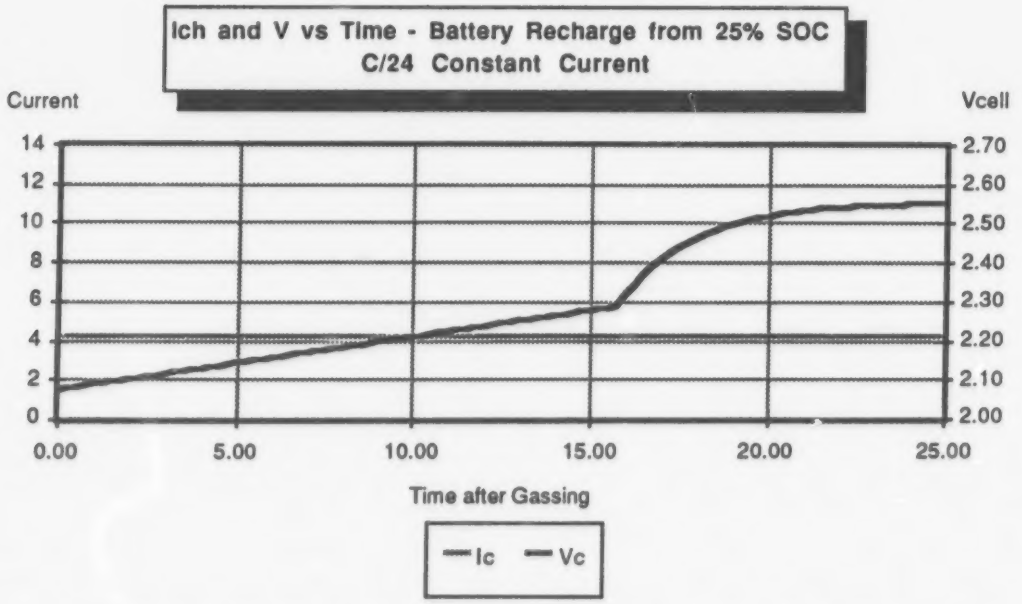

FIGURE 4-9B ICH & V VS TIME - C/24 CONSTANT CURRENT

4.3. Recharge Efficiencies

The amp-hour recharge efficiencies of the various methods can be measured by dividing the number of amp-hour needed to bring the battery to 95% SOC by the number of amp-hours that are produced by the charger during this time period. The energy efficiency (kWh) can be estimated the same way. An example of the efficiency during recharge is shown in Figure 4-10. Note how the instantaneous efficiency starts to really drag the net efficiency down after 90% SOC. Another way of examining this same problem is to plot the efficiency times the battery SOC versus battery SOC, as shown in Figure 4-11. Note the clear peak at around 90% state of charge. This verifies the reasoning behind limiting diesel charge to 95% SOC except during periodic equalizations.

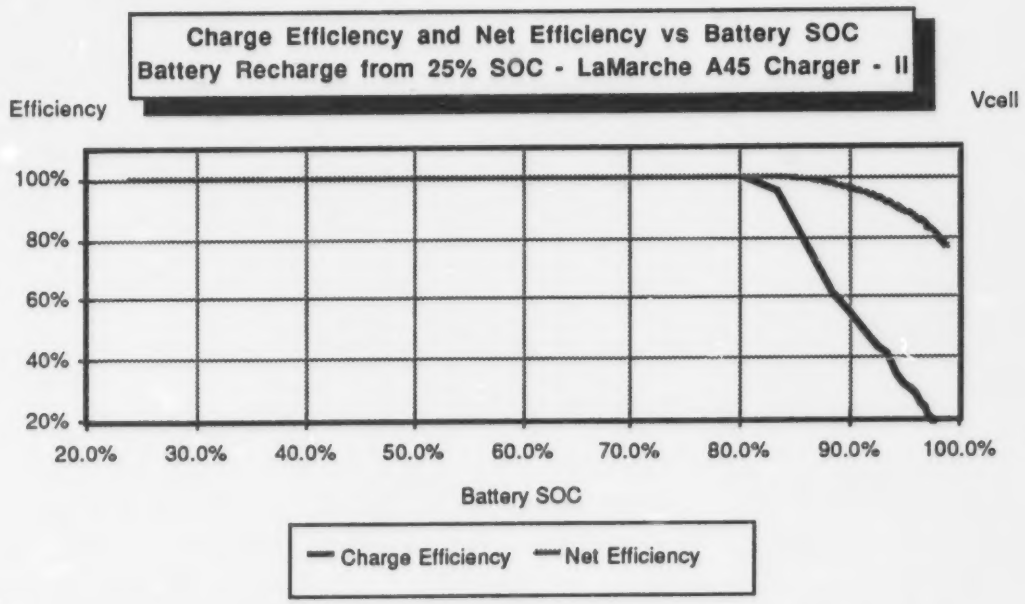

FIGURE 4-10 RECHARGE EFFICIENCY - MODIFIED A45 CHARGER

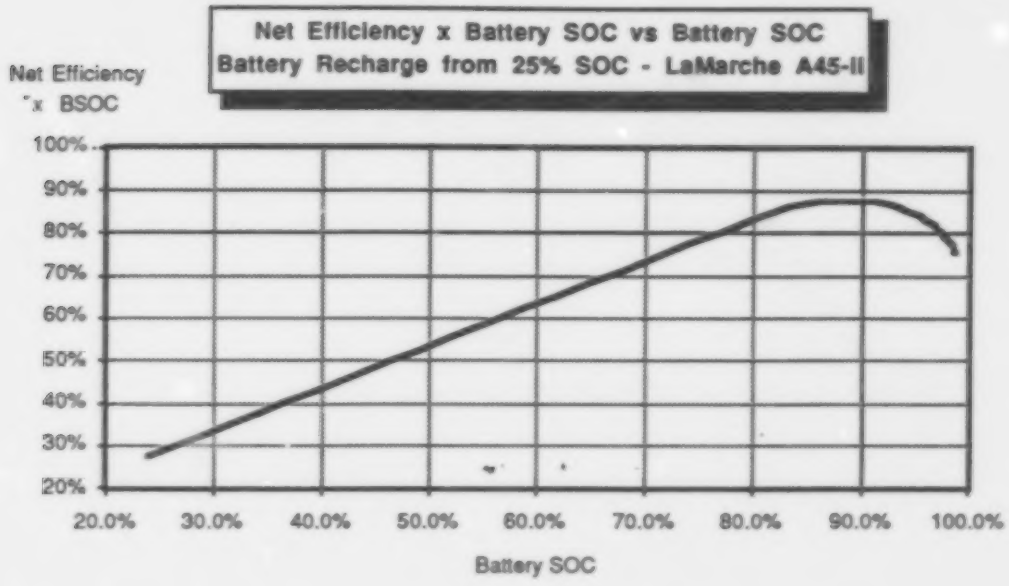

FIGURE 4-11 CYCLIC CHARGE EFFICINCY-END OF CHARGE EFFECT

The charge efficiency for each of the methods proposed in Section 4.2 is shown in Figure 4-12. Note that the efficiency tends to be inversely proportional to the recharge time. This is further verified by examining the round trip energy efficiency of a battery under differing charge/discharge profiles. For example, a 24 hour discharge from 95% to 25% followed by a recharge using the adjusted LaMarche charger has a round trip energy efficiency (Wh in ÷ Wh out) of only 56%, while the same discharge followed by a 24 hour recharge to 95% has a Wh efficiency of 89%. This difference in efficiency is made up for by the fact that the diesel has to run 250% as long for the 24 hour recharge as the quick recharge. Since maintenance and replacement, which are directly proportional to operating hours, accounts for over 70% of life cycle operating costs in the baseline system (fuel is the other 30%), this is an important factor indeed.

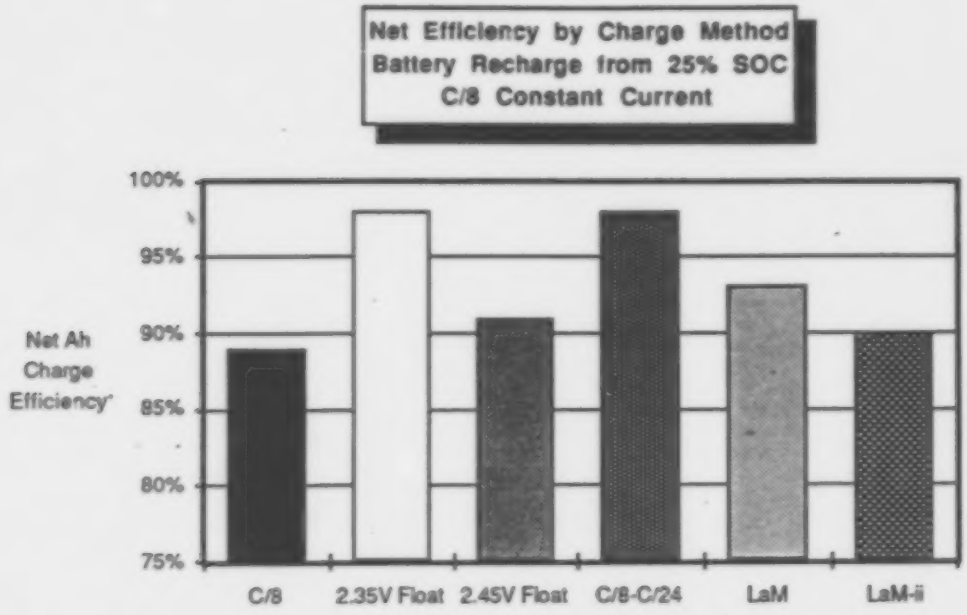

FIGURE 4-12 RECHARGE EFFICIENCY BY METHOD

4.4. Optimized Charge Method

The two goals for optimizing the recharge algorithm are minimized diesel operating time, and recharge efficiency. The high rate recharge with a voltage limit is the clear choice with the first requirement, while a slower rate has a clearly higher efficiency, but runs the diesel generator for excessive lengths of time. The final decision is based on life cycle cost of the two methodologies. A comparison of systems incorporating the fast and slow recharge procedures (Figure 4-13) shows clearly that the fast recharge system has an advantage over the slow recharge system, due to the high cost of diesel maintenance.

System Description	Diesel Cycles (#/yr)	Diesel Hours (#/yr)	Diesel Fuel Use (L/yr)	Operating Cost (C$/yr)	LCC Enery Cost (C$/kWh)
C/8 Recharge	85	526	2,636	$4,000	$0.98
C/24 Recharge	75	1,628	2,647	$6,553	$1.16

FIGURE 4-13 FAST / SLOW RECHARGE COMPARISON

4.5. Control Hardware Requirements

Due to the mathematical nature of this algorithm, a microprocessor based controller must be used in the hybrid system. This controller should have the following inputs at a minimum: battery voltage, battery current, array current, load current, rectifier current, and battery temperature. It should have the ability to regulate two subarrays, and two separate loads, as well as starting, stopping, and exercising the diesel generator. The rectifier must be controllable both as a current limited source and a voltage limited source. This function would ideally be managed by the system controller, but it can be performed by a separate controller in the battery charge rectifier provided there is some communications between the two control systems.

The controller should operate in a continuous loop, monitoring the inputs and adjusting the outputs on a real time basis. The system needs to be monitored at least once per second, and should have appropriate digital and analog filtering on all inputs to prevent system electrical noise from affecting control decisions.

The power requirements of this type of hardware system require the use of large DC rated switchgear and fault protection. In the baseline system, the maximum array current is 75 amperes at 48 VDC, the rectifier current is 145 amperes peak, and the maximum inverter DC input current is 125 amps DC. The maximum current at any point in the system is 220 amps on the battery line when both the array and the rectifier are charging at full capacity and there is no load. These currents can be brought down significantly through the use of a system with a 120 volt nominal battery. Typically, a 48 volt system would be used for dedicated DC telecom loads, while a 120 volt system would be used for systems using inverters.

5. Conclusions / Recommendation

5.1 Recommended System Configuration

In order to choose an optimum system, a large number of different designs were analyzed using the hybrid sizing program. These systems had variations in generator/rectifier size, in battery size, and in solar contribution. Both capital and life cycle costs were calculated for each system. Special attention was paid to maintenance requirements, and to replacement of batteries as a function of cycle life.

The final recommendation is a system incorporating a 84 kWh flooded lead acid battery (2.6 days at the 72 hour rate), a 4.7 kWp PV array, and a 17.3 kWh diesel generator using a 245 amp controlled rectifier to charge batteries. The batteries are cycled regularly between 25% and 95% SOC with one equalization cycle every six cycles. Annual operation shows 85 diesel starts for a total operation time of only 526 hours per year. Peak fuel consumption on the generator is 5.6 liters per hour, with an annual fuel consumption of 2,636 liters.Recommended maintenance is one visit per year plus an emergency visit four of every five years.The engine would only need to be overhauled once during the 25 year life of the system, and the batteries also need to be replaced only once. This data is summarized in Figure 5-1.

SOLCAD - RAPS Remote Area Power Supply Sizing Program

Integrated Power Corporation - copyright 1990

System Summary

Site:	Moosonee Lake, Ontario, Canada		
Date:	23 Mar 90		
Load:	24 kWh/day @	120 V AC	
Battery:	Type	E120-29	
	Voltage	48 V DC	
	Amp-hrs	1750	@ 72 hr rate
	Capacity	2.6 days	
		84 kWh	
PV Array:	Module	M-47	47 W(p)
	# of Modules	100	
	Array Rating	4.70 kW(p)	
Diesel Genset:	Type	Lister TR3	
	Rating	17.3 kWe	
	Frequency	60 hz	
Wind Turbine:	Type		
	Rating	0.0 kW	
Diesel Performance	Cycles	85	
	Hours	526	
	Fuel Use	2,636	
Energy Contribution	PV	44.2%	
	Wind	0.0%	
	Diesel	55.8%	
Cost Information	Capital	$129,643	
	Operating	$4,000	
	Life Cycle	$0.979	

FIGURE 5-1 PERFORMANCE SUMMARY - RECOMMENDED SYSTEM

The system has a projected capital cost of $129,643, annual maintenance costs of $4,000 (including $1,582 for fuel and $2,418 for maintenance visits and overhauls), and a life cycle cost of C$0.979 per kWh. Figure 5-2 shows the life cycle cost summary for the recommended system.

LIFE CYCLE COST ANALYSIS

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Description	24 kWh/day Hybrid Recommended System
Analysis Period	25 yrs

Components	$113,643
Shipping	$2,000
Installation	$4,000
Distribution	
Project Management	$10,000
Total Capital	$129,643
% Financed	0%
Amount Financed	$0
Loan Term	25 yrs
Loan Interest	10.0%
Loan Payments	$0
Energy Produced	24 kWh/day

Discount Rate	10.0%
Fuel Escalation	8.0%
Fuel Esc Ratio	0.982
Non-Fuel Escalation	6.0%
Non-Fuel Esc Ratio	0.964
Fuel Use	2,636
Fuel Cost per Litre	$0.60
Recurring Fuel	$1,582
Recurring Non-Fuel	$2,418

Non-Recurring Item	Amount	Year
Battery	$23,824	13

Item	Amount	Year	Factor	LCC
Capital	$129,643	0	1.000	$129,643
Loan Payment	$0	all	25.000	$0
Recurring Fuel	$1,582	all	19.867	$31,422
Recurring Non-Fuel	$2,418	all	16.003	$38,700
Battery	$23,824	13	0.618	$14,719
	$0	0	1.000	$0
	$0	0	1.000	$0
	$0	0	1.000	$0
	$0	0	1.000	$0

Total LCC	$214,484
Total Energy	219,000
Unit Cost	$0.979

FIGURE 5-2 LIFE CYCLE COST SUMMARY - RECOMMENDED SYSTEM

5.2 Recommended Control Algorithm

The recommended control algorithm incorporates the high rate (C/8) charge regime with some voltage limiting (either the 2.45 volt float charger or the adjusted traction battery charger is appropriate). The rectifier controller should be able to manage a full and constant charge rate to the battery despite normal variations on the load during the charging period. The cycling should occur between 25% and 95% SOC, with and equalizing charge once every six cycles (about once per month) to bring the batteries up to full capacity.

Control Algorithm

Discharge

1. Discharge battery to 25% SOC using Eqs 3.1 & 3.2 to monitor state of charge at variable discharge rates, then start generator.
2. If constricted generator operation is in effect (i.e. daytime operation only), then discharge only to 40% SOC before setting flag to start generator. Start generator when operational window starts or battery SOC falls to 25%, whichever comes first.
3. If voltage falls to 1.80 volts per cell, start generator in either case.
4. If SOC falls below 25%, set low voltage alarm (because of gen failure or whatever).
5. If SOC falls below 22%, disconnect non-priority loads.
6. If SOC falls below 20%, disconnect all loads.

Recharge

1. Calculate gassing voltage as function of charge rate using Eq 3.4
2. If voltage is below gassing voltage, use Eqs 3.3 - 3.6 to determine SOC.
3. If voltage is above gassing voltage, use Eqs 3.4 - 3.5 & 3.9 - 3.10 to determine SOC.
4. If SOC rises to 30%, reconnect priority loads.
5. If SOC rises to 40%, reconnect all loads.
6. If battery voltage rises to 2.45 V/cell, taper rectifier to maintain 2.45 volts per cell.
7. When SOC = 95%, turn off rectifier, cool generator down and turn off generator.
8. If battery voltage rises to 2.42 volts per cell disconnect Array 1
9. If battery voltage rises to 2.43 volts per cell, disconnect Array 2
10. If battery voltage falls to 2.32 volts per cell, reconnect Array 2.
11. If battery voltage falls to 2.30 volts per cell, reconnect Array 1.
12. If battery voltage rises to 2.48 volts per cell, set off high voltage alarm, and disconnect all charge relays immediately.

Further analysis is needed to determine whether the charge rate can be increased to C/5 safely and economically. Special attention needs to be paid to the interaction of the PV array and rectifier during periods where they are both charging.

Sealed batteries also need additional study. Although preliminary testing showed that they are capable of accepting high rates of discharge and are fairly tolerant to overcharging, not enough is known about the long term effects of fast charging on the cells. If sealed batteries are incorporated into a hybrid system, careful attention should be paid to choosing an appropriate charge rate and battery size. Sealed batteries offer excellent possibilities for use in hybrid systems if their behavior can be sufficiently characterized to allow their use.

5.3 Generic Design

This study has concentrated on a 24 kWh per day load as the baseline system, but in commercial practice, hybrid systems are being used to supply loads ranging from 5 kWh/day to many hundreds of kWh/day. This section presents a generic design methodology for designing a hybrid system to meet a specific load and estimating annual performance. This is intended to be a sizing exercise, many of the performance details require calculations far in excess of the scope of this study.

Step 1 - CALCULATE LOAD IN AMP-HRS PER DAY.

$$Load(Ah/d) = kWh/day \div Vavg \quad (9.1)$$

where $Vavg$ = average load voltage = 2.15 V/cell (9.2)

Step 2 - CALCULATE BATTERY SIZE

$$BatterySize(Ah) = (Ah/day \times 2.5) \div MaxDOD \quad (9.3)$$

where $MaxDOD = 80\%$ (9.4)

$$BatterySize(kWh) = BatterySize(Ah) \times Vbatt \quad (9.5)$$

where $Vbatt$ = Battery Voltage (9.6)

Step 3 - CALCULATE RECTIFIER AND GENERATOR SIZE

$$RectifierSize(A) = BatterySize(AH) \div MaxRate \quad (9.7)$$

where $MaxRate = C/8$ (9.8)

$$GeneratorSize(kVA) = RectifierSize(AH) \times Vch \div P.F. \quad (9.9)$$

where Vch = charge voltage = 2.45 V/cell (9.10)

and $P.F.$ = Rectifier Power Factor (9.11)

Step 4 - CALCULATE ARRAY SIZE

*ArraySize(A) = (Load(Ah/d) * PV%) ÷ (Insol x EffA)*	9.12
where *PV% = % annual PV contribution*	9.13
and *Insol = Annual avg Solar Insolation in kWh/m²/day*	9.14
and *EffA = efficiency of Array*	9.15
ArraySize(kWp) = (ArraySize(A) ÷ Im) x (Vbatt ÷ 12) x Wm	9.16
and I_m = *PV Module Operating Current*	9.17
and W_m = *PV Module Peak Wattage*	9.18

Step 5 - CALCULATE GENERATOR HOURS AND FUEL CONSUMPTION

GeneratorHrs =	
*LoadAH/day * 365 * (1-PV%) ÷ RectifierSize ÷ EffCycle*	9.19
where *EffCycle = Recharge Cycle Efficiency*	9.20
*FuelUse(L) = GeneratorHrs * DEGFC*	9.21
where *DEGFC = Fuel consumption of actual DEG at load*	9.22

Technical Glossary of Terms

Array A photovoltaic array is usually the full complement of photovoltaic modules, complete with wiring and mounting structure, at a site.

Amp-hours (Ah) A measure of current over time. Typically used to rate battery capacity.

Battery State of Charge (SOC) or (BSOC) The available capacity of a battery expressed as a percentage of rated capacity. A battery discharged 30% is at 70% SOC.

Commercial Application A demanding, rigorous specification for critical loads. Typical commerical projects are telecommunications, railroads and oil/gas. In many countries these are called "professional" projects.

Counter EMF (CEMF) Cell A devce using series diodes to lower the voltage presented to a load during battery recharging. Typically used in telecommunications appliactions.

Cycling The process of discharging and recharging a battery, also involving a diesel start in a hybrid system.

Depth of Discharge (DOD) Depth of discharge. Used to describe level of battery discharge from full state-of-charge. DOD = 1 – BSOC.

Finishing Rate The charge current at the end of a battery recharge period.

Finishing Voltage The battery voltage at the end of a battery recharge period.

Float Batteries Batteries used in appliactions requiring emergency backup. These batteries are typically left connected to a charger at all times with a very low charge current supplied to the batteries. This technique is called "floating" the batteries.

Float Voltage The voltage at which standby batteries are held in order to maintain optimum charge and minimum water loss.

Flooded Battery A battery in which the electrolye is in liquid form, and access is provided to the electrolye for replacement, etc. A complementary type of battery is a "sealed" battery.

Gassing The process occurring at the end of lead acid battery recharges where water is dissociated into oxygen and hydrogen gas.

Hybrid The combination of two or more power generation technologies to form a single power system.

Insolation The total solar radiation-direct, diffuse and reflected- received on a surface over a period of time. Usually experessed in kilowatt-hours per square meter (also known as "sun-hours").

Inverter A device used to convert direct current electricity (typically from a battery) into alternating current electricity.

Kilowatt (kW) A unit of power equal to 1000 watts.

Kilowatt-hour (kWh) A unit of energy (power over time) equal to 1000 watt-hours.

Module, photovoltaic A group of solar cells wired and sealed into an environmentally protected package. The smallest replaceable unit in a PV array.

Peak power point The point on a PV cell, module or array's I-V curve at which the product of a current and voltage are maximum. This is the point at which the device produces "peak" or maximum power.

Peak watt (W_p) A unit of power expressing the amount of power produced by a PV module, cell or array at Standard Test Conditions.

Photovoltaic (PV) A solid state process used to generate electricity from light using a semiconductor.

Prime Diesel A diesel used to provide the primary source of power to a given load. Typically operates 24 hours per day.

Rate of charge/discharge The battery charge/discharge current divided by the battery capacity. Typically expressed as C/24 which means capacity in Ah divided by 24 hours.

Rectifier An electronic device which converts (rectifies) AC electricity into DC electricity, either for use directly by the load, or for battery charging.

Sealed Battery A battery in which the electrolyte is not available in liquid form. Sealed batteries come in two generic types - absorbed electrolyte, in which the electrolyte is held captive in a pourous mat somehwat like a sponge, and gelled electrolyte, in which the electrolyte is gelled with an extrenal compound. In reality, "sealed" lead acid batteries are not sealed - they have a pressure activated vent, and thus are often referred to as "valve-regulated" batteries in the technical literature.

Standalone system A non-hybrid PV power system that is independent of the utility grid or any other power source.

Trickle Charging See "Float Charging."

Uninterruptible Power Supply (UPS) An electronic system which uses a battery, a rectifier and usually an inverter to guarantee a supply of electricity to a dedicated load.

Appendix A - Life Cycle Costing Methodology

DEVELOPMENT OF PV DIESEL HYBRID SYSTEM DESIGN INCORPORATING ADVANCED CONTROL ALGORITHMS

LIFE CYCLE COST SUMMARY

1. METHODOLOGY

Life cycle costing methodology, where all capital, recurring, and non-recurring costs are brought to present day value using discount and escalation factors. The life cycle cost is presented in two forms. The first is the total life cycle costs for the system under analysis. This is the total of the capital and discounted operating costs for the system during the term of the analysis. The second form is the unit life cycle energy cost. This is the discounted cost per kilowatt hour of energy produced by the system.

2. CONSTANTS

2.1. Life Cycle Term (n)

Life cycle term = n = 25 years

The life cycle period is defined as the longest life of any major item, with shorter lived items covered by replacement. Since the PV modules lhave a projected lifetime of 25 years, this has been chosen as the life cycle term.

2.2. Discount Rate (r)

Discount Rate = r = 10% per annum

2.3. Fuel Escalation (a_f)

Fuel Escalation = a_f = 8 % per annum

Fuel Escalation Factor is defined as:

$$Esc_f = (1 + a_f) / (1 + r) = 0.982$$

2.4. Non-Fuel Escalation (a_{nf})

Non-Fuel Escalation = a_{nf} =6% per annum

Non-fuel Escalation Factor is defined as:

$$Esc_{nf} = (1 + a_{nf}) / (1 + r) = 0.964$$

2.5. Fuel Price

Fuel Cost = $0.60 per liter, delivered to the site.

2.6. Wages

Mechanics wages are $35 per hour
Assistants wages are $25 per hour
Site per diem is $35 per day

2.7. Travel to Site

Typical travel to site is $100 per person per site visit. This covers truck travel to the site for a crew of two for routine maintenance.

3. COSTS

3.1. Capital Costs

We have assumed that capital costs are expended in full in period 0 (before the start of operation).

Therefore the discount multiplier is 1.0.

3.2. Recurring Fuel Costs

The formula for calculating recurring fuel costs is :

$$LCC_f = C_f * [1 - (Esc_f \wedge n)] / [(1 / Esc_f) - 1]$$
$$= 19.867$$

where

C_f = Annual Fuel Use * Fuel Price

3.3. Recurring Non-Fuel Costs

The formula for calculating recurring non-fuel costs is :

$$LCC_{nf} = C_{nf} * [1 - (Esc_{nf} \wedge n)] / [(1 / Esc_{nf}) - 1]$$
$$= 16.002$$

where

$C_{nf} = \sum_{i=1,j}$ (Maintenance and Repair Costs)

3.4. Non-Recurring Costs

The formula for calculating recurring non-fuel costs is :

$$LCC_{Non\text{-}recurring} = \sum_{i=1,k} C_i * [(1 + a_{nf}) \wedge t_i] / [(1 + r) \wedge t_i]$$

$$= 0.831 \text{ (5 years)}$$
$$= 0.690 \text{ (10 years)}$$
$$= 0.574 \text{ (15 years)}$$
$$= 0.477 \text{ (20 years)}$$

where

C_i = Individual non-recurring cost, and

t_i = Year in which C_i is expended

for "k" individual items.

3.4.1. Batteries

Replacement of batteries includes 20% addition for shipping, handling and disposal of old cells.

3.4.2. Generators

Generator replacement shipping and disposal costs are assumed to be minimal

3.4.3. Other

3.4.4. Frequent Non-recurring Costs

Frequent non-recurring costs can be amortized into non-fuel recurring costs by dividing the cost by the period of occurrence.

For example, if a diesel generator needs an overhaul every 18 months, and the cost is $1,000 , then the recurring cost is $1000 / 1.5 yrs = $667 per yr .

3.5 Total Life Cycle Cost (LCC$)

The life cycle energy cost is the total cost of operating the system over the term of the analysis, and is defined as follows:

$$LCC\$ = \text{Capital Costs} + LCC_f + LCC_{nf} + \sum \text{Non-recurring}$$

3.6 Unit Energy Cost

Life cycle unit energy cost is a measure of the relative cost of energy produced, without relation to the system size. It has the units of dollars per kilowatt-hour ($/kWh), and is defined as follows:

$$C_{energy} = LCC\$ \,/\, (\text{Energy produced per year} * \text{Life Cycle Term})$$

4.0 COMPUTER ASSISTED ANALYSIS

4.1 MS-DOS Based Spreadsheet

4.2 Macintosh Based Spreadsheet

Appendix B - System Design Summaries

Baseline System Performance Summary

SOLCAD - RAPS **Remote Area Power Supply Sizing Program**

Integrated Power Corporation - copyright 1990

System Summary

Site:	Moosonee, Ontario, Canada	
Date:	23 Mar 90	
Load:	24 kWh/day @	120 V AC
Battery:	Type	E120-29
	Voltage	48 V DC
	Amp-hrs	1750 @ 72 hr rate
	Capacity	2.6 days
		84 kWh
PV Array:	Module	M-47 47 W(p)
	# of Modules	100
	Array Rating	4.70 kW(p)
Diesel Genset:	Type	Lister TR2
	Rating	11.5 kWe
	Frequency	60 hz
Wind Turbine:	Type	
	Rating	0.0 kW
Diesel Performance	Cycles	81
	Hours	887
	Fuel Use	2,702
Energy Contribution	PV	44.2%
	Wind	0.0%
	Diesel	55.8%
Cost Information	Capital	$128,065
	Operating	$5,321
	Life Cycle	$1.069

Notes:

Input Data - Load and Climate

Load Summary

AC Load (kWh/day)	24.0
Load (avg watts)	1,000
AC Voltage	120
Inverter Efficiency	85%
Inverter Size (kVA)	7.5
DC Load (W cont)	0.0
DC/DC Converter eff	90%
Total DC Load (kWh/day)	28.2
Total DC Load (avg DC watts)	1,176
System DC Voltage (nominal)	48
Avg Load Voltage (2.15 Vpc)	51.6
Load Type ([P]ower/[C]urrent)	C
Load (avg DC amps)	24.5
Load (Ah/day)	588.2
Annual Load (Ah - DC)	214,706
Daily Load (kWh - DC)	28.2
Annual Load (kWh - DC)	10,306

Climatic Data

Month	Solar Insol (kWh/m2)	Avg Temp (deg C)	Wind Velocity (m/s)	avg Vw 0.0
Jan	3.13	25.0	0.0	0.0
Feb	4.70	28.0	0.0	0.0
Mar	5.16	30.0	0.0	0.0
Apr	5.04	30.0	0.0	0.0
May	4.55	32.0	0.0	0.0
Jun	4.79	33.0	0.0	0.0
Jul	4.54	30.0	0.0	0.0
Aug	4.12	29.0	0.0	0.0
Sep	3.48	27.0	0.0	0.0
Oct	2.47	25.0	0.0	0.0
Nov	1.86	25.0	0.0	0.0
Dec	2.42	25.0	0.0	0.0
Avg	3.86	28.3	0.0	0
Max	5.16	33.0	0.0	
Min	1.86	25.0	0.0	

AC Load Profile

Load Class Time Period	Load (kW)
00:00 - 01:00	0.40
01:00 - 02:00	0.25
02:00 - 03:00	0.25
03:00 - 04:00	0.35
04:00 - 05:00	0.35
05:00 - 06:00	0.45
06:00 - 07:00	1.00
07:00 - 08:00	1.25
08:00 - 09:00	1.30
09:00 - 10:00	1.10
10:00 - 11:00	1.05
11:00 - 12:00	1.10
12:00 - 13:00	1.05
13:00 - 14:00	1.00
14:00 - 15:00	1.10
15:00 - 16:00	1.40
16:00 - 17:00	1.55
17:00 - 18:00	1.70
18:00 - 19:00	2.20
19:00 - 20:00	1.50
20:00 - 21:00	1.45
21:00 - 22:00	1.40
22:00 - 23:00	0.50
23:00 - 24:00	0.30
Load (kWh/day):	24.00

Input Data - Components

PV Module

Module Type	M-47
Peak Watts	47
I_nom (a)	3
Modules per string	4
# of Strings {Input}	25

Diesel Electric Generator

Engine Type	Lister TR2
Rated Power (kWe)	11.5
Power Factor	0.8
Rated kVA	14.4
Rated Frequency (hz)	60
Max Operating Temp (°C)	30.0
Temperature Derating	0.4%
Operating Altitude (m)	250
Altitude Derating	1.2%
Operating Humidity	50.0%
Humidity Derating	0.0%
Total Derating	1.5%
Net Output (kWe)	11.3
Net Output (kVA)	14.2
Full Load FC (L/hr)	3.7
1/4 Load FC (L/hr)	1.5
FC Factor	2.96

Diesel Battery Charger

Stage 1	Current	145
	Eff	85%
	P.F.	0.7
Stage 2	Current	109
	Eff	82%
	P.F.	0.7
Stage 3	Current	83
	Eff	80%
	P.F.	0.7

Station Battery

Individual Cell	
Manufacturer:	
Type	E120-29
Rating - 8 hr	1479
Rating - 24 hr	1750
Rating - 72 hr	1890
Volts per Cell	2
Battery Derating	0%
Full Battery Bank	
# of strings	1
# of cells	24
Rating - 8 hr	1,479
Rating - 24 hr	1,750
Rating - 72 hr	1,890
Rating - Actual	1,890
Days of Storage to 80%	2.6

Wind Turbine

Manufacturer	
Model	
Peak Output	0.0 kW
K Factor	2.8
Turbulence Derating	11%
Altitude Derating	3%

Subsystem Performance Calculations

System

System Voltages (Avg)	Vpc	VDC
System Voltage (nom)	2.00	48.0
Avg Load Voltage	2.15	51.6
Diesel Charge - Stage 1	2.25	54.0
Diesel Charge - Stage 2	2.35	56.4
Diesel Charge - Stage 3	2.45	58.8
PV Charge	2.30	55.2
Wind Charge	2.30	55.2

Wind Turbine Performance

Weibull Calcs			
V avg	0.00	Density	0.97
K Factor	2.80	Turb	0.89

V (m/s)	Dsgn %kW	Prob. (f)	Net kW
1.0	0%	0.00	0.00
2.0	0%	0.00	0.00
3.0	3%	0.00	0.00
4.0	8%	0.00	0.00
5.0	16%	0.00	0.00
6.0	34%	0.00	0.00
7.0	43%	0.00	0.00
8.0	55%	0.00	0.00
9.0	63%	0.00	0.00
10.0	74%	0.00	0.00
11.0	83%	0.00	0.00
12.0	100%	0.00	0.00
13.0	100%	0.00	0.00
14.0	100%	0.00	0.00
15.0	120%	0.00	0.00
16.0	120%	0.00	0.00
17.0	120%	0.00	0.00
18.0	120%	0.00	0.00
19.0	120%	0.00	0.00
20.0	120%	0.00	0.00
Total Probability =		0.00	
Mean Power Output (MPO, in kW) =			0.00

Annual Energy Contribution

Month	Velocity (m/s)	MPO kW
Jan	0.0	0.0
Feb	0.0	0.0
Mar	0.0	0.0
Apr	0.0	0.0
May	0.0	0.0
Jun	0.0	0.0
Jul	0.0	0.0
Aug	0.0	0.0
Sep	0.0	0.0
Oct	0.0	0.0
Nov	0.0	0.0
Dec	0.0	0.0
Avg	0.0	0.0

PV Array Energy Calcs

Total # of Mods	100
Array Rating - kW(p)	4.7
Avg Insol (kWh/m2/day)	3.86
PV Losses	10%
String Current (amps)	3.0
Full Array Current (amps)	75.0
String Output (Ah/day)	10.4
Full Array Output (Ah/day)	260.2
Avg Annual PV Contribution	44.2%

Wind Turbine Energy Calcs

Avg WEG Output (W)	0
WEG Derating	20%
Net WEG Output (W)	0
Net WEG Output (amps)	0.0
Max WEG Output (amps)	0.0
WEG Ah/day	0.0
WEG kWh/day	0.0
Avg WEG Contribution	0.0%

DEG Loading Calcs

Stage	kW Load	kVA Load
1	9.2	13.2
2	7.5	10.7
3	6.1	8.7

Stage	% kW Load	% kVA Load
1	81%	93%
2	66%	75%
3	54%	61%

Stage	Fuel Consumption
1	3.1 l/hr
2	2.7 l/hr
3	2.3 l/hr

Controller Sizing

Circuit	Max Amperage
Array	145.0
WTG	0.0
Rectifier	145.0
Load	183.8
Battery Line	290.0

Battery Charging Performance Calculations

Cycle Depth Info

BSOC	Ah remaining
100%	1,890
95%	1,796
85%	1,607
25%	473

Charging Stages

Stage#	Range	Eff	Net Ah
1	25% to 85%	99%	1,145
2	85% to 95%	97%	195
3	95% to 100%	90%	105

Max Battery Charge/Discharge Loading

Charge				Max Rate
Stage#	DEG	WEG	PV	
1	145	0	75	0.15 C8
2	108.75	0	75	0.12 C8
3	83	0	75	0.11 C8
Discharge		Inverter		
		184		0.12 C8

Cycle Info

Stage	Duration	Diesel Ah	Fuel
1	8:38	1,241	27.2
2	2:01	213	5.5
3	1:29	111	3.5
Total - norm	10:39	1,454	32.7
Total - eq	12:09	1,565	36.1
Normal Cycles		5	
Equalize Cycles		1	
Avg Cycle Duration		10:54	
Avg Cycle Ah		1,473	
Avg Cycle Fuel (L)		33.2	

DEG Energy Calcs

Avg DEG Contribution	55.8%
Annual DEG Contribution (Ah)	119,728
Avg Cycle Ah	1,473
Annual Cycles	81.3
Annual Operating Time (hrs)	887
Annual Fuel Consumption (L)	2,702

Battery Cycle Calcs

Stage 1 DEG amps	145.0
WEG amps	0.0
PV amps	12.0
Load amps	-24.5
Net amps	132.5
Cycle AH	1145
Cycle Time	8:38
Stage 2 DEG amps	108.8
WEG amps	0.0
PV amps	12.0
Load amps	-24.5
Net amps	96.3
Cycle AH	195
Cycle Time	2:01
Stage 3 DEG amps	82.5
WEG amps	0.0
PV amps	12.0
Load amps	-24.5
Net amps	70.0
Cycle AH	105
Cycle Time	1:29

Annual Performance Calculations

Monthly Ah Contribution Breakdown

Month	# of Days	Load Ah	PV Ah	Wind Ah	Diesel Ah	Diesel Cycles	Diesel Hours
Jan	31	18,235	6,550	0	11,686	7.9	87
Feb	28	16,471	8,883	0	7,588	5.2	56
Mar	31	18,235	10,797	0	7,438	5.1	55
Apr	30	17,647	10,206	0	7,441	5.1	55
May	31	18,235	9,521	0	8,714	5.9	65
Jun	30	17,647	9,700	0	7,947	5.4	59
Jul	31	18,235	9,500	0	8,735	5.9	65
Aug	31	18,235	8,621	0	9,614	6.5	71
Sep	30	17,647	7,047	0	10,600	7.2	79
Oct	31	18,235	5,168	0	13,067	8.9	97
Nov	30	17,647	3,767	0	13,881	9.4	103
Dec	31	18,235	5,064	0	13,171	8.9	98
Total	365	214,706	94,823	0	119,883	81.4	889
Avg	30	17,892	7,902	0	9,990	6.8	74

Monthly Energy Contribution Breakdown

Month	% PV	% Wind	% Diesel	PV kWh	Wind kWh	DEG kWh
Jan	36%	0%	64%	267	0	477
Feb	54%	0%	46%	362	0	310
Mar	59%	0%	41%	441	0	303
Apr	58%	0%	42%	416	0	304
May	52%	0%	48%	388	0	356
Jun	55%	0%	45%	396	0	324
Jul	52%	0%	48%	388	0	356
Aug	47%	0%	53%	352	0	392
Sep	40%	0%	60%	288	0	432
Oct	28%	0%	72%	211	0	533
Nov	21%	0%	79%	154	0	566
Dec	28%	0%	72%	207	0	537
Avg	44.2%	0.0%	55.8%	3,869	0	4,891

Other Cost Calculations

FUEL COST CALCS

Base Fuel Cost	$0.60
Fuel Delivery per L per km	$0.003
Distance (km)	0
Actual Fuel Cost	$0.60

ANNUAL OPERATING COSTS

Item		Qty	Cost /Unit		Item Total	$/hr
1.	Diesel Fuel	2,702	$0.60	L	$1,621.44	$1.83
2.	Operator	0	$0.00	day	$0.00	$0.00
2.	Maintenance Visits	2.8	$1,283	ea.	$3,609.10	$4.07
3.	Diesel Overhaul	0.09	$1,000	ea.	$90.00	$0.10
				Subtotal	$5,320.54	$6.00

LCC ANALYSIS

Life Cycle Term		25 yrs		Repl 1	13
Discount Rate		10%		Repl 2	999
Fuel Inflation		8%	0.982		
Other Inflation		6%	0.964		
ITEM		COST		Factor	ITEM TOT
1.	Capital Costs	$128,065		1.00	$128,065
2.	Fuel	$1,621		19.87	$32,214
3.	Maintenance / Operation	$3,699		16.00	$59,196
4.	Batt Repl 1	$23,824		0.62	$14,719
5.	Batt Repl 2	$23,824		0.00	$0

Life Cycle Cost	$234,194
Daily Energy (kWh)	24.0
Total Energy (kWh)	219,000
Unit ($/kWh)	$1.07

Recommended System Performance Summary

SOLCAD - RAPS **Remote Area Power Supply Sizing Program**

Integrated Power Corporation - copyright 1990

System Summary - Recommended System

Site:	Moose Lake, Ontario, Canada		
Date:	23 Mar 90		
Load:	24 kWh/day @	120 V AC	
Battery:	Type	E120-29	
	Voltage	48 V DC	
	Amp-hrs	1750	@ 72 hr rate
	Capacity	2.6 days	
		84 kWh	
PV Array:	Module	M-47	47 W(p)
	# of Modules	100	
	Array Rating	4.70 kW(p)	
Diesel Genset:	Type	Lister TR3	
	Rating	17.3 kWe	
	Frequency	60 hz	
Wind Turbine:	Type		
	Rating	0.0 kW	
Diesel Performance	Cycles	85	
	Hours	526	
	Fuel Use	2,636	
Energy Contribution	PV	44.2%	
	Wind	0.0%	
	Diesel	55.8%	
Cost Information	Capital	$129,643	
	Operating	$4,000	
	Life Cycle	$0.979	

Notes:

	Cap Cost	$/kWh	PV %
	$129,643	$0.979	44.2%
11	$108,266	$1.073	19.5%
17	$117,281	$1.073	30.1%
23	$126,631	$0.980	40.7%
28	$134,160	$0.979	49.5%
34	$143,194	$0.978	60.2%
40	$152,544	$0.978	70.8%
45	$160,073	$0.976	79.6%

Input Data - Load and Climate

Load Summary

AC Load (kWh/day)	24.0
Load (avg watts)	1,000
AC Voltage	120
Inverter Efficiency	85%
Inverter Size (kVA)	7.5
DC Load (W cont)	0.0
DC/DC Converter eff	90%
Total DC Load (kWh/day)	28.2
Total DC Load (avg DC watts)	1,176
System DC Voltage (nominal)	48
Avg Load Voltage (2.15 Vpc)	51.6
Load Type ([P]ower/[C]urrent)	C
Load (avg DC amps)	24.5
Load (Ah/day)	588.2
Annual Load (Ah - DC)	214,706
Daily Load (kWh - DC)	28.2
Annual Load (kWh - DC)	10,306

AC Load Profile

Load Class Time Period	Load (kW)
00:00 - 01:00	0.40
01:00 - 02:00	0.25
02:00 - 03:00	0.25
03:00 - 04:00	0.35
04:00 - 05:00	0.35
05:00 - 06:00	0.45
06:00 - 07:00	1.00
07:00 - 08:00	1.25
08:00 - 09:00	1.30
09:00 - 10:00	1.10
10:00 - 11:00	1.05
11:00 - 12:00	1.10
12:00 - 13:00	1.05
13:00 - 14:00	1.00
14:00 - 15:00	1.10
15:00 - 16:00	1.40
16:00 - 17:00	1.55
17:00 - 18:00	1.70
18:00 - 19:00	2.20
19:00 - 20:00	1.50
20:00 - 21:00	1.45
21:00 - 22:00	1.40
22:00 - 23:00	0.50
23:00 - 24:00	0.30
Load (kWh/day):	24.00

Climatic Data

Month	Solar Insol (kWh/m2)	Avg Temp (deg C)	Wind Velocity (m/s)	avg Vw 0.0
Jan	3.13	25.0	0.0	0.0
Feb	4.70	28.0	0.0	0.0
Mar	5.16	30.0	0.0	0.0
Apr	5.04	30.0	0.0	0.0
May	4.55	32.0	0.0	0.0
Jun	4.79	33.0	0.0	0.0
Jul	4.54	30.0	0.0	0.0
Aug	4.12	29.0	0.0	0.0
Sep	3.48	27.0	0.0	0.0
Oct	2.47	25.0	0.0	0.0
Nov	1.86	25.0	0.0	0.0
Dec	2.42	25.0	0.0	0.0
Avg	3.86	28.3	0.0	0
Max	5.16	33.0	0.0	
Min	1.86	25.0	0.0	

Input Data - Components

PV Module

Module Type		M-47
Peak Watts		47
I_nom (a)		3
Modules per string		4
# of Strings	*(Input)*	25

Diesel Electric Generator

Engine Type	Lister TR3
Rated Power (kWe)	17.3
Power Factor	0.8
Rated kVA	21.6
Rated Frequency (hz)	60
Max Operating Temp (°C)	30.0
Temperature Derating	0.4%
Operating Altitude (m)	250
Altitude Derating	1.2%
Operating Humidity	50.0%
Humidity Derating	0.0%
Total Derating	1.5%
Net Output (kWe)	17.0
Net Output (kVA)	21.2
Full Load FC (L/hr)	5.6
1/4 Load FC (L/hr)	2.2
FC Factor	4.44

Diesel Battery Charger

Stage 1	Current	245
	Eff	85%
	P.F.	0.8
Stage 2	Current	184
	Eff	82%
	P.F.	0.8
Stage 3	Current	123
	Eff	80%
	P.F.	0.7

Station Battery

Individual Cell	
Manufacturer:	
Type	E120-29
Rating - 8 hr	1479
Rating - 24 hr	1750
Rating - 72 hr	1890
Volts per Cell	2
Battery Derating	0%
Full Battery Bank	
# of strings	1
# of cells	24
Rating - 8 hr	1,479
Rating - 24 hr	1,750
Rating - 72 hr	1,890
Rating - Actual	1,890
Days of Storage to 80%	2.6

Wind Turbine

Manufacturer	
Model	
Peak Output	0.0 kW
K Factor	2.8
Turbulence Derating	11%
Altitude Derating	3%

Subsystem Performance Calculations

System

System Voltages (Avg)	Vpc	VDC
System Voltage (nom)	2.00	48.0
Avg Load Voltage	2.15	51.6
Diesel Charge - Stage 1	2.25	54.0
Diesel Charge - Stage 2	2.40	57.6
Diesel Charge - Stage 3	2.45	58.8
PV Charge	2.30	55.2
Wind Charge	2.30	55.2

Wind Turbine Performance

Weibull Calcs			
V avg	0.00	Density	0.97
K Factor	2.80	Turb	0.89

V (m/s)	Dsgn %kW	Prob. (f)	Net kW
1.0	0%	0.00	0.00
2.0	0%	0.00	0.00
3.0	3%	0.00	0.00
4.0	8%	0.00	0.00
5.0	16%	0.00	0.00
6.0	34%	0.00	0.00
7.0	43%	0.00	0.00
8.0	55%	0.00	0.00
9.0	63%	0.00	0.00
10.0	74%	0.00	0.00
11.0	83%	0.00	0.00
12.0	100%	0.00	0.00
13.0	100%	0.00	0.00
14.0	100%	0.00	0.00
15.0	120%	0.00	0.00
16.0	120%	0.00	0.00
17.0	120%	0.00	0.00
18.0	120%	0.00	0.00
19.0	120%	0.00	0.00
20.0	120%	0.00	0.00
Total Probability =		0.00	
Mean Power Output (MPO, in kW) =			0.00

Annual Energy Contribution

Month	Velocity (m/s)	MPO kW
Jan	0.0	0.0
Feb	0.0	0.0
Mar	0.0	0.0
Apr	0.0	0.0
May	0.0	0.0
Jun	0.0	0.0
Jul	0.0	0.0
Aug	0.0	0.0
Sep	0.0	0.0
Oct	0.0	0.0
Nov	0.0	0.0
Dec	0.0	0.0
Avg	0.0	0.0

PV Array Energy Calcs

Total # of Mods	100
Array Rating - kW(p)	4.7
Avg Insol (kWh/m2/day)	3.86
PV Losses	10%
String Current (amps)	3.0
Full Array Current (amps)	75.0
String Output (Ah/day)	10.4
Full Array Output (Ah/day)	260.2
Avg Annual PV Contribution	44.2%

Wind Turbine Energy Calcs

Avg WEG Output (W)	0
WEG Derating	20%
Net WEG Output (W)	0
Net WEG Output (amps)	0.0
Max WEG Output (amps)	0.0
WEG Ah/day	0.0
WEG kWh/day	0.0
Avg WEG Contribution	0.0%

DEG Loading Calcs

Stage	kW Load	kVA Load
1	15.6	19.5
2	12.9	16.1
3	9.0	12.9

Stage	% kW Load	% kVA Load
1	92%	92%
2	76%	76%
3	53%	61%

Stage	Fuel Consumption
1	5.2 l/hr
2	4.5 l/hr
3	3.5 l/hr

Controller Sizing

Circuit	Max Amperage
Array	245.0
WTG	0.0
Rectifier	245.0
Load	183.8
Battery Line	490.0

Battery Charging Performance Calculations

Cycle Depth Info

BSOC	Ah remaining
100%	1,890
95%	1,796
85%	1,607
25%	473

Charging Stages

Stage#	Range	Eff	Net Ah
1	25% to 85%	99%	1,145
2	85% to 95%	97%	195
3	95% to 100%	90%	105

Max Battery Charge/Discharge Loading

Charge				
Stage#	DEG	WEG	PV	Max Rate
1	245	0	75	0.22 C8
2	183.75	0	75	0.17 C8
3	123	0	75	0.13 C8
Discharge		Inverter		
		184		0.12 C8

Cycle Info

Stage	Duration	Diesel Ah	Fuel
1	4:55	1,195	25.5
2	1:08	203	5.1
3	0:57	105	3.3
Total - norm	6:03	1,398	30.6
Total - eq	7:01	1,503	33.9
Normal Cycles		5	
Equalize Cycles		1	
Avg Cycle Duration		6:13	
Avg Cycle Ah		1,415	
Avg Cycle Fuel (L)		31.2	

DEG Energy Calcs

Avg DEG Contribution	55.8%
Annual DEG Contribution (Ah)	119,728
Avg Cycle Ah	1,415
Annual Cycles	84.6
Annual Operating Time (hrs)	526
Annual Fuel Consumption (L)	2,636

Battery Cycle Calcs

Stage 1 DEG amps	245.0
WEG amps	0.0
PV amps	12.0
Load amps	-24.5
Net amps	232.5
Cycle AH	1145
Cycle Time	4:55
Stage 2 DEG amps	183.8
WEG amps	0.0
PV amps	12.0
Load amps	-24.5
Net amps	171.3
Cycle AH	195
Cycle Time	1:08
Stage 3 DEG amps	122.5
WEG amps	0.0
PV amps	12.0
Load amps	-24.5
Net amps	110.0
Cycle AH	105
Cycle Time	0:57

Annual Performance Calculations

Monthly Ah Contribution Breakdown

Month	# of Days	Load Ah	PV Ah	Wind Ah	Diesel Ah	Diesel Cycles	Diesel Hours
Jan	31	18,235	6,550	0	11,686	8.3	51
Feb	28	16,471	8,883	0	7,588	5.4	33
Mar	31	18,235	10,797	0	7,438	5.3	33
Apr	30	17,647	10,206	0	7,441	5.3	33
May	31	18,235	9,521	0	8,714	6.2	38
Jun	30	17,647	9,700	0	7,947	5.6	35
Jul	31	18,235	9,500	0	8,735	6.2	38
Aug	31	18,235	8,621	0	9,614	6.8	42
Sep	30	17,647	7,047	0	10,600	7.5	47
Oct	31	18,235	5,168	0	13,067	9.2	57
Nov	30	17,647	3,767	0	13,881	9.8	61
Dec	31	18,235	5,064	0	13,171	9.3	58
Total	365	214,706	94,823	0	119,883	84.7	527
Avg	30	17,892	7,902	0	9,990	7.1	44

Monthly Energy Contribution Breakdown

Month	% PV	% Wind	% Diesel	PV kWh	Wind kWh	DEG kWh
Jan	36%	0%	64%	267	0	477
Feb	54%	0%	46%	362	0	310
Mar	59%	0%	41%	441	0	303
Apr	58%	0%	42%	416	0	304
May	52%	0%	48%	388	0	356
Jun	55%	0%	45%	396	0	324
Jul	52%	0%	48%	388	0	356
Aug	47%	0%	53%	352	0	392
Sep	40%	0%	60%	288	0	432
Oct	28%	0%	72%	211	0	533
Nov	21%	0%	79%	154	0	566
Dec	28%	0%	72%	207	0	537
Avg	44.2%	0.0%	55.8%	3,869	0	4,891

Other Cost Calculations

FUEL COST CALCS

Base Fuel Cost	$0.60
Fuel Delivery per L per km	$0.003
Distance (km)	0
Actual Fuel Cost	$0.60

ANNUAL OPERATING COSTS

Item		Qty	Cost	/Unit	Item Total	$/hr
1.	Diesel Fuel	2,636	$0.60	L	$1,581.82	$3.00
2.	Operator	0	$0.00	day	$0.00	$0.00
2.	Maintenance Visits	1.8	$1,283	ea.	$2,368.55	$4.50
3.	Diesel Overhaul	0.05	$1,000	ea.	$50.00	$0.09
				Subtotal	$4,000.37	$7.60

LCC ANALYSIS

Life Cycle Term		25 yrs		Repl 1	13
Discount Rate		10%		Repl 2	999
Fuel Inflation		8%	0.982		
Other Inflation		6%	0.964		
ITEM		COST		Factor	ITEM TOT
1.	Capital Costs	$129,643		1.00	$129,643
2.	Fuel	$1,582		19.87	$31,427
3.	Maintenance / Operation	$2,419		16.00	$38,703
4.	Batt Repl 1	$23,824		0.62	$14,719
5.	Batt Repl 2	$23,824		0.00	$0
			Life Cycle Cost		$214,491
			Daily Energy (kWh)		24.0
			Total Energy (kWh)		219,000
			Unit ($/kWh)		$0.98